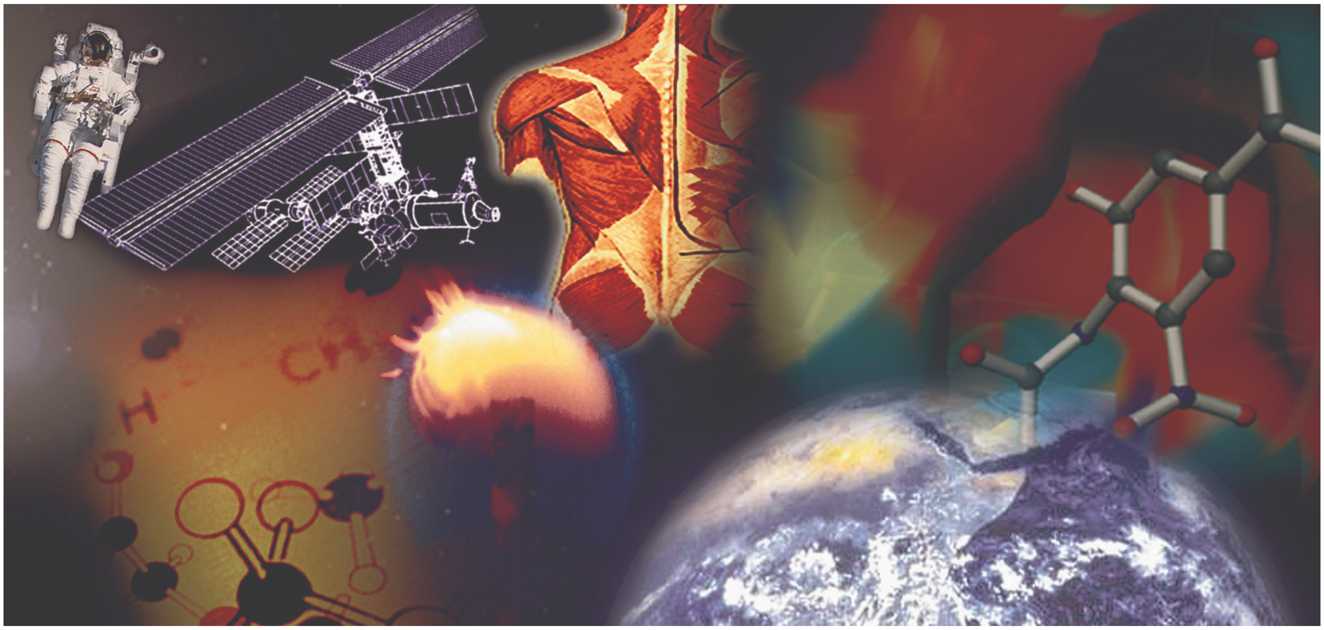
OBPR'S RESEARCH PLAN



Our Past Orbit, Our Current Orbit -- And Beyond

April 10, 2003

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Executive Summary

This Research Plan presents the mission, acknowledges the past accomplishments, and clarifies the priorities and intended direction for scientific investigations, strategic research, and commercial and technological developments to be sponsored by NASA's Office of Biological and Physical Research. The audience for this Plan is intended to be the relevant research communities, agency and federal management, and Congressional interests. It was prepared in response to Congressional direction (e.g. HR.106-988, S.107-222) for a ten-year research plan that includes operational requirements for the research to be done on the International Space Station (ISS).

For over 40 years, NASA has sent people on short forays in orbit to conduct brief scientific and engineering experiments in apparent weightlessness, i.e. in microgravity. We sought to understand the role of gravity in the physical universe and on life itself. We learned that the effects of gravity that we experience on Earth significantly alter the behavior of many aspects of biology, physics and chemistry. We also learned that biological systems – from cells to plants to people -- undergo changes from short-term and long-term space habitation that are not completely understood. Thus, humankind's eventual travel beyond earth's orbit into new environments poses profound challenges. We must discover ways for space explorers to withstand hazards for which humanity's experience on Earth never prepared them. As we discover, we also will seek new knowledge, technology, and commerce to realize benefits for people on earth, and innovations that enable scientific exploration safely, productively, and affordably.

The OBPR and its predecessor organization have had a successful history of spaceflight research in life and microgravity sciences. Flagship missions flew successfully on the Shuttle and the Mir, in anticipation of the creation of the International Space Station. These programs, which evolved into the OBPR research portfolio of today, nearly doubled in the last 6 years—from fewer than 350 to greater than 1,000 research investigations. The published journal articles and patented technologies reflect this growth. In 2001, our 852 principal investigators produced 3,499 research publications. Similarly, the commercial programs grew over the same time period -- from nascent entities to a set of commercial space centers that today are working with 150 US companies and 80 product lines in multiple disciplines.

For the first time, the laboratory of the International Space Station (ISS) offers scientists and engineers a permanent microgravity facility with much more power, crew time, and physical volume than the Space Shuttle, the Mir, or any other laboratory. As stated by the NASA Administrator, "*The International Space Station (ISS) is without precedent in the history of the U.S. space program… In the unique environment of space combined with research, exploration, human innovation and creativity, the ISS holds the potential to forever improve the quality of life on Earth.*"

The Office of Biological and Physical Research endeavors to lead our research to realize this potential – not only in the ISS, but in all of our experiments in space. The environment on the ISS and other space-based laboratories makes the research supported in this Office unique to the NASA mission, and separates it from the research by other agencies.

The OBPR Mission

NASA has a new Vision: *To improve life here, to extend life to there, to find life beyond*. Our contribution to the Agency to realize this Vision is written as a Mission Statement that motivates our research on the ISS and is the framework for the activities of OBPR:

Humans will extend the exploration of space. To prepare for and hasten the journey, OBPR must answer these questions through its research:

- **How can we assure survival of humans traveling far from earth?**
- **What must we know about how space changes life forms, so that humankind will flourish?**
- **What new opportunities can our research bring to expand understanding of the laws of nature and enrich lives on Earth?**
- **What technology must we create to enable the next explorers to go beyond where we have been?**
- **How can we educate and inspire the next generations to take the journey?**

This Research Plan provides a top-level description of the OBPR direction to answer these questions and fulfill our mission. The answers will not come easily. A systematic approach, utilizing a combination of national, international and commercial resources (both on earth and in space) and a clear stable investment strategy are required. These questions engender more detailed questions and still more detailed research plans and roadmaps. For example, the above questions are further delineated in the following table:

ORGANIZING QUESTION	DETAILED QUESTIONS / TOPICS
Question 1: How can we assure survival of humans traveling far from earth?	What knowledge, tools and procedures are needed to enable best practices for providing medical care in space?
	How does the human body adapt to space flight, to what extent do these adaptive responses compromise crew health, safety, and performance during and after space flight, and what are the most effective and efficient techniques to counteract those adaptive responses that place crewmembers at unacceptable levels of risk?
	How can we protect human space explorers from the harmful health affects associated with exposure to space flight radiation environments?
	How can we provide an optimal environment to support behavioral health and human performance in space flight and afterwards?
Question 2: What must we know about how space changes life forms, so that humankind will flourish?	Does space affect life at its most fundamental levels, from the gene to the cell?
	How does long-term exposure to space affect organisms?
	How does space affect the development and lifecycles of organisms?
	How do systems of organisms and their interactions change in space?
Question 3: What new opportunities	How does the space environment change the behavior of physical and chemical processes and the technologies that rely on them?
	What can we learn about the organizing principles from which structure and complexity arise in nature?

can our research bring to expand understanding of the laws of nature and enrich lives on Earth?	Where can our research advance our knowledge of the fundamental laws governing time and matter?
	What are the fundamental physical, chemical, and biophysical mechanisms that drive the cellular and physiological behavior observed in the space environment?
	How can research partnerships – both market-driven and interagency -- support national goals, such as contributing to economic growth and sustaining human capital in the areas of science and technology?
Question 4: What technology must we create to <u>enable</u> the next explorers to go beyond where we have been?	What research and technology development is required to reduce the required up-mass, volume, and power of the next generation of autonomous, highly reliable spacecraft sub-systems?
	What research is required to develop safe, efficient and economical in-space transportation for travel beyond LEO?
	What research and technology innovation is required to provide affordable, abundant power for operations, including the utilization of in-situ planetary resources?
	What research and technology development is needed in automated sensing, and autonomous controls architecture to ensure that the crew is living in a safe and healthy environment?
	What research and technology development must be achieved to enable optimum crew performance and productivity during extended isolation from Earth?
Question 5: How can we <u>educate</u> and <u>inspire</u> the next generations to take the journey?	Educational Outreach
	Public Outreach

While the past demonstrated the merits of our research and validated the concept of an orbital laboratory, new areas of emphasis will carry OBPR beyond microgravity-based, curiosity-driven studies into a strategic research thrust that includes topics such as radiation health and protection, bioastronautics, and technology aimed at sustained human exploration of space. For humans to venture into and to explore space beyond where they have been, NASA must be able to provide the same kind of safe environmental cocoon for space explorers that Earth provides for us. The challenge begins with safe and renewable air, water, and food. A sufficient depth of understanding of how humans and other life forms adapt to the effects of space flight is essential to provide appropriate medical support tools to maintain human health. To enable this, and to ensure that we understand physical and biological processes in space well enough to exploit them safely, OBPR must provide an integrated research product that answers the key questions in our mission. The OBPR's sponsorship of research, therefore, is evolving to focus on answering these questions. Research roadmaps – both general and specific – will form the basis of time-phased competitive solicitations for research and technology and our research activities on the ISS.

The human exploration of space is one of the great voyages of discovery in human history. This is why it is both so compelling and so challenging. It must be anticipated that explorers will encounter many unforeseen difficulties as well as many opportunities that are beyond our current vision. We must make sure that they have the tools and knowledge available to respond to the challenges they encounter in creating habitats and using the resources available to them in new environments. The biomedical, biological, scientific and engineering research communities bring critical talents to this effort, and represent a segment in the national fabric of science, engineering, and education that must be enlisted in order to assure the long-term success of the Enterprise. This community has a long history of participation in other mission-driven research efforts. In collaboration with NASA's own researchers, this community will continue to be the centerpiece upon whom we rely to develop research and technology that has high scientific merit, significant terrestrial benefit and/or direct relevance to NASA’s mission needs.

Foreword

This research plan presents the mission, acknowledges the past accomplishments, and clarifies the priorities and intended direction for scientific investigations, strategic research, commercial and technological developments to be sponsored by NASA's Office of Biological and Physical Research (OBPR). The audience for this plan is intended to be the relevant research communities, agency and federal management, and Congressional interests. It was prepared in response to Congressional direction (e.g. H.R.106-988, S.107-222) for a ten-year research plan that includes operational requirements for the research to be done on the International Space Station (ISS).

The OBPR Research Plan was also prepared to guide, unify and stabilize the endeavors of this new NASA Enterprise, which receives many recommendations from advisory committees, technical societies, international partners, and a vested public. The plan relies and builds upon the work of our predecessors, our peers and external advisors, such as the NASA Advisory Council, the Research Maximization and Prioritization (ReMaP) Task Force, the Independent Management and Cost Evaluation (IMCE) committee, and several National Research Council (NRC) panels. In issuing this plan, we hope to engage the scientific and engineering research communities to realize the potential benefits of the new laboratories in space, especially those on the ISS.

A draft of this research plan was issued in December, 2002 for review and comment by the OBPR advisory committees and subcommittees, as well as placed on the OBPR Web site for open review. Comments were also solicited from the research community attending various technical conferences. To the extent possible, those comments were incorporated into the final research plan herein.

This document will serve as the basis for more detailed plans and open, competitive solicitations for research to answer the 'Organizing Questions'. The more detailed plans will be developed and vetted with the research community. The detailed plan development and the associated vetting process may cause the phrasing of the 'sub-questions' to be changed. A goal is for the detailed plans and the implementation plans of the OBPR to be finalized by the end of the 2003 fiscal year.

Introduction

For over 40 years, NASA has sent people on short forays in orbit to conduct brief scientific and engineering experiments in apparent weightlessness, i.e. in microgravity. We sought to understand the role of gravity in the physical universe and on life itself. We learned that the effects of gravity that we experience on Earth limit our knowledge of many aspects of biology, physics and chemistry. We also learned that biological systems – from cells to plants to people -- undergo changes from short-term and long-term space habitation that are not completely understood. Thus, humankind's eventual travel beyond earth's orbit into new environments poses profound challenges. We must discover ways for space explorers to withstand hazards for which humanity's experience on Earth never prepared them. As we discover, we also will seek new knowledge, technology, and commerce to realize benefits for people on earth, and innovations that enable scientific exploration safely, productively, and affordably.

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The Office of Biological and Physical Research endeavors to lead our research to realize this potential – not only in the ISS, but also in all of our experiments in space.

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NASA has a new Vision: *To improve life here, to extend life to there, to find life beyond*. Our contribution to the Agency to realize this Vision is written as a Mission Statement that motivates our research on the ISS and is the framework for the activities of OBPR:

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The ISS provides us both a unique opportunity and a unique obligation in our nation's history to perform our mission. For at least the next fifteen years, it is the centerpiece of our laboratories in space. Our findings and accomplishments must reach the public to inform and satisfy them with the return on their investment in our research. Through our research, we continuously seek to obtain:

- New knowledge, technology, and commerce to realize benefits for people on Earth
- Innovations that enable NASA 'to extend life to there' safely, productively, and affordably.

The environment on the ISS and other space-based laboratories makes the research supported by this Office unique to the NASA mission, and separates it from the research by other agencies.

This Research Plan provides a top-level description of the OBPR direction to answer these questions and fulfill our mission. The answers will not come easily. A systematic approach, utilizing a combination of national, international and commercial resources (both on earth and in space) and a clear stable investment strategy are required. The nature of the challenges described here make inter-disciplinary effort essential for success.

More detailed plans for each Organizing Question, with associated Performance Metrics, are being developed over the coming year. The following sections of this Research Plan contain:

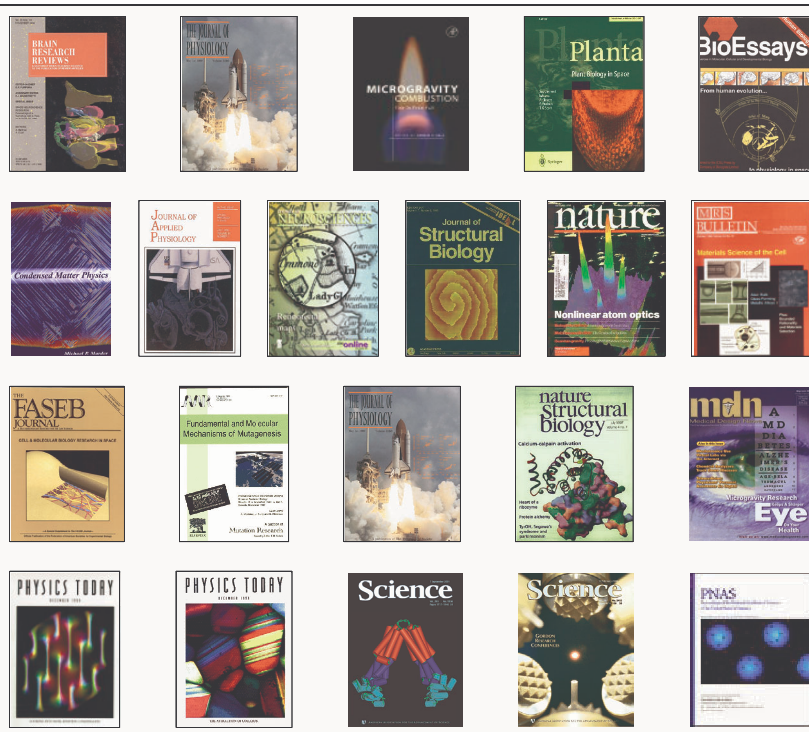
> **Our Past Orbit**: highlights of OBPR's research accomplishments, technological innovations, and educational and public outreach activities from laboratories on earth, in the Shuttle, and in the ISS.
>
> **Our Current Orbit -- and Beyond**: where we are going: implementation and further prioritization of Research Maximization and Prioritization (REMAP) Task Force recommendations – which research areas will be emphasized, which will be de-emphasized, development of key questions and a research framework for ISS utilization (including the primary products or outputs and the desired outcomes, and the top-level roadmaps related to the questions)
>
> **Accomplishing Our Mission**: our interdisciplinary future; the ten-year plan for ISS utilization; innovations to make the spaceflight process more efficient; guiding principles; introduction to performance metrics
>
> **Summary**

Appendices: A. Descriptions of OBPR Research Thrusts (per OBPR-prepared material for ReMaP Task Force); B. Details of A Ten Year Model: The Use of ISS

OUR PAST ORBIT

In 1996, the following words appeared in the NASA microgravity science plan: “Over the next few years, the character of the microgravity science program will be one of exploration and discovery to more clearly define the specific areas of research that will become the foundation of a recognized and respected program of research in space. This should not be a program based on serendipity, but an orchestrated process or sequence of steps designed to probe and use space in ways to carry out research to benefit the people of the United States and the international community.”

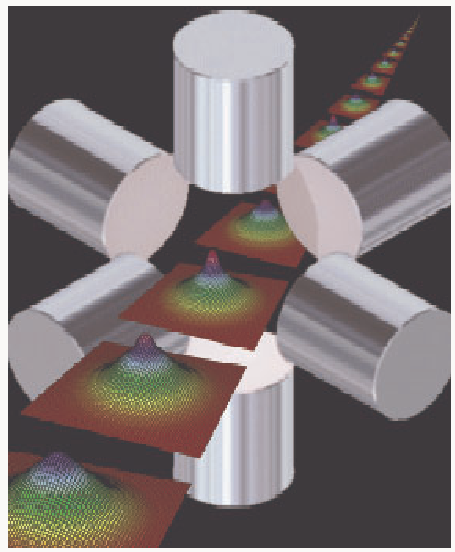
Six years later, it is clear that the microgravity and life sciences programs, as they were formerly known, kept faith with this idea. Flagship missions flew successfully on the Shuttle and the Mir, in anticipation of the creation of the International Space Station. These programs, which evolved into OBPR’s terrestrial and space-based research portfolio of today, nearly doubled in the last 6 years—from fewer than 350 to greater than 1,000 research investigations. The published articles and patented technologies reflect this growth. In 2001, our 852 principal investigators produced 3,499 research publications. Similarly, the commercial programs grew over the same time period -- from nascent entities to a set of commercial space centers that today are working with 160 US companies and 80 product lines in multiple disciplines. The investigators’ credentials are broad and deep, ranging from winners of the Presidential Early Career Awards for Scientists and Engineers to members of the National Academy of Sciences and National Academy of Engineering to laureates of the Nobel Prize.



OBPR Research has appeared on the covers of major scientific journals and books.

We are proud of the discoveries and products that were made by experimentation in space and on earth, and here highlight a few of them from the Shuttle and earth-based laboratories and then from the ISS. The findings from many of these experiments are mentioned as exemplary in the recent National Research Council reports (e.g. the 2002 Assessment of Directions in Microgravity and Physical Sciences Research at NASA).

<u>From Our Research in Earth and Shuttle Laboratories</u>



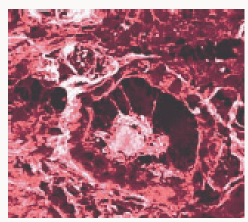
Slowing down atoms enough to produce a Bose-Einstein condensate is a tricky undertaking that involves the trapping and cooling of atoms to extremely low temperatures. (In this artist's rendering, time progresses from the lower left to the upper right corner. Six cylinder shaped magnets keep the atoms in place as they cool to a condensate, shown as the central peaks in this series of images.)

Bose Einstein Condensation Research: The 2001 Nobel Prize for physics was awarded to three scientists, including a Massachusetts Institute of Technology physicist whose NASA-funded research uses ultra-cold atoms that form a new type of matter. The Royal Swedish Academy of Sciences said Dr. Wolfgang Ketterle and two other scientists caused atoms to "sing in unison." Through their research, atomic particles were induced to have the same energy and to oscillate together in a controlled fashion. Laser light has these qualities, but researchers have struggled for decades to make matter behave this way. The breakthrough research has potential uses for extremely precise measurements. The discoveries may lead to microscopic computers and ultra-precise gyroscopes that could dramatically improve aircraft guidance and spacecraft navigation. They can be used in atomic beam deposition for chip production (atom lithography), and may also allow fabrication of extremely sophisticated nanostructures. When atoms are cooled to temperatures near the absolute zero, they become 'de-localized', and at a given temperature and density, collectively condense into a single quantum entity called a Bose-Einstein Condensate (BEC). Atoms extracted from a Bose-Einstein Condensate (BEC) exhibit coherence, the same property of photons in a conventional laser. A Bose Einstein Condensate was used to produce the first atom laser.

Bone Loss Research: Scientists showed mild vibrations prevent bone loss that normally occurs in hind-limb suspended rats, a ground-based animal model of unloading. The technique works by stimulating the bones' stress response. A team of researchers, led by Dr. Clinton Rubin of the State University of New York at Stony Brook, discovered that normally active animals exposed to 10 minutes per day of low-magnitude, high-frequency vibrations experienced increased bone formation when compared to a control group. In addition, when animals, prevented from regular, weight-bearing activity, were exposed to 10 minutes of vibrations per day, bone formation remained at near-normal levels. Animals not exposed to the treatment, but who participated in 10 minutes of weight-bearing activity each day, still exhibited signs of significant bone loss. While preliminary results are encouraging, a full clinical study must be completed to demonstrate the effectiveness of using vibrations to recover bone mass and architecture in people with osteoporosis or to prevent the bone loss known to occur in astronauts during long duration space flight.

Persuading turkeys to stand on a vibrating platform for several minutes a day was only one of the many challenges facing Clinton Rubin in his research of the mechanisms of bone loss.

High-Fidelity Models of Tissues: The first high fidelity models of tissues were produced for cartilage, heart, and kidney based on NASA-developed technology and research. These three-dimensional tissue models have important implications for the field of tissue engineering with respect to future transplantation therapies, drug testing, and bio-molecule synthesis. The level of fidelity found in these engineered tissues was reflected in their morphological and molecular structures that paralleled those found in the body.



Under an interagency agreement, the NASA-NIH Center for Three-Dimensional Tissue Culture has developed advanced prostate cancer models for drug testing based on NASA technology that provides unique advantages for biomedical research.

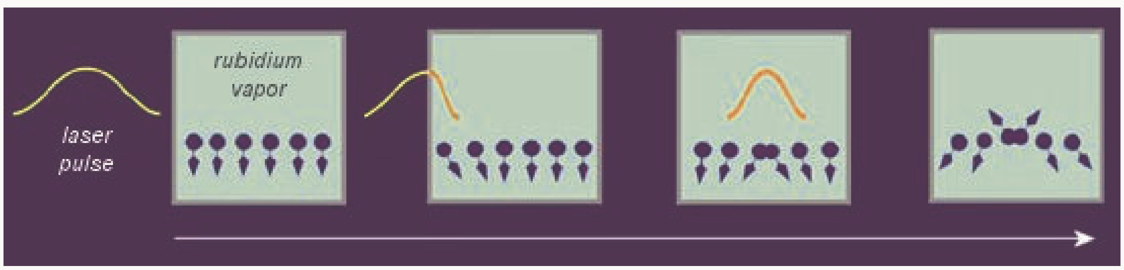
An Internal Model of Gravity: Neurolab flight research suggests our mind contains an internal model of gravity that we use to anticipate acceleration in performing motor tasks such as ball catching – this model may be "hardwired", i.e. the sensory-motor system appears unable to adapt quickly to the lack of gravity.

Playing catch is easy. Kids and even their parents can do it. Keep your eyes on the ball and -- if you don't think too hard -- your hand will grab it in mid-air. It's simple, really. Or is it? In fact, playing catch is more complicated than it appears.

Weakest Flames Ever Observed: The weakest flames (less than 1 watt) ever to exist were produced in Shuttle flights, providing the unique observation of Flame Balls (stationary, spherical flames that were hypothesized by the renowned Russian scientist, Yakov Zel'dovich, about sixty years ago but never observed until these experiments). By comparison a birthday candle flame is about fifty watts. According to the Principal Investigator, Prof. Paul Ronney of the University of Southern California, the results should help scientists seeking to improve modeling of hydrogen-oxygen-diluent chemical reaction rates necessary for a wide range of fuel-efficient combustion processes.

Flame balls that form in low gravity are hard to see. These were filmed in the dark by a low-light video camera onboard the space shuttle in 1997.

Stopping Light: Light was stopped, held, and sent on its way in the laboratory by OBPR-sponsored researchers. Light normally speeds along at about 300,000 kilometers



As the laser pulse enters the chamber containing the rubidium vapor, the information that defines the light becomes imprinted on the atoms' spin states (indicated by the small arrows). In the moment that the light is "stopped," only the spin states exist.

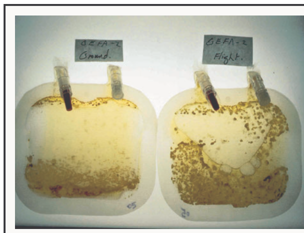
per second. Nothing in the universe moves faster, and Albert Einstein theorized that nothing ever could. Recent experiments performed at Harvard University brought a pulse of laser light to a dead stop inside a cloud of atoms -- and released it again intact. The light went into a glass chamber filled with atomic vapor, but it didn't come out again until summoned. It was not destroyed or absorbed, but rather stored -- ready to emerge intact at the scientists' bidding. Such command of light could lead to new technologies which exploit the bizarre rules of quantum mechanics -- the laws of nature that govern light and matter on atomic scales -- to enable perfectly secure communication and tremendous increases in computing speed. Scientists envision using the stopped light technique to connect ultra-fast quantum computers in a large ultra-secure network analogous to the Internet.

Gravity-sensitive Fertilization Processes: Processes associated with fertilization were demonstrated in spaceflight to be gravity-sensitive. Sperm of sea urchins became activated to swim more quickly in microgravity than they did on Earth. Conversely, in an experiment conducted on Earth, activation was reduced when the sperm were exposed in a centrifuge to a gravitational force greater than normal earth gravity. Furthermore, the rate of binding of sperm to eggs and fertilization itself were considerably reduced with centrifuged sperm.

A scanning electron micrograph of numerous sperm morphologies on Earth.

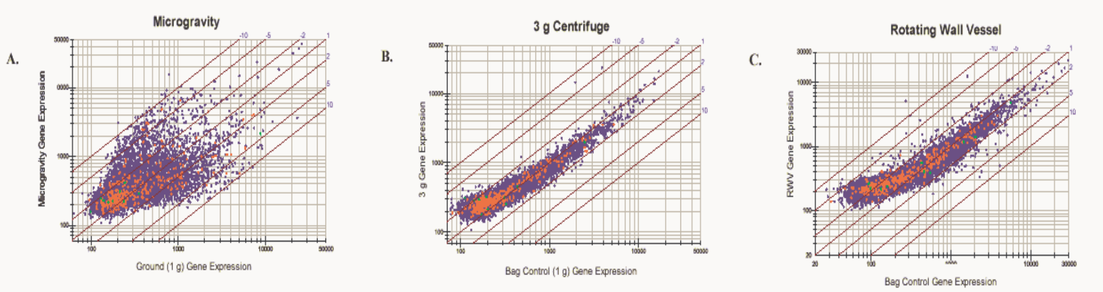
Discovery of A Window of Non-Flammability: Drop tower and Shuttle experiments showed that there are conditions that will sustain a flame in microgravity, whereas no flame exists for these same conditions on earth. Also found quite remarkably was a window of non-flammability, a notion that was completely unpredicted: on earth, as one dilutes a reactive mixture, it is always rendered non-flammable; in microgravity, very relevant conditions were found that a nonflammable mixture was rendered flammable again with additional dilution – this has been seen only in microgravity. The importance of these experiments cannot be overstated, according to National Academy of Engineering members Chung K. Law and Gerard Faeth: *"Thus, any notion that flammability limits for gases at normal gravity are applicable to conditions at microgravity is erroneous. Additional measurements of lean flammability limits for a wider range of reactants are clearly needed to provide the technology base required for safe spacecraft operation with respect to fires and explosions."*

Antibiotic Production in Microgravity: Bristol-Myers Squibb and the Center for BioServe Space technologies demonstrated microbial production of antibiotics is substantially greater in microgravity than on earth. In one case the improvement was as much as 200%. The research goal is simple: to find out why microbes yield more antibiotics on orbit, and apply those findings to increase yields on Earth. The production of antibiotics represents an extremely large and profitable enterprise for the U.S. pharmaceutical industry. With the global market in excess of $23 billion, its production has a significant impact on this Nation's economic competitiveness and well-being. Bristol-Myers Squibb is committing increasing amount of cash and in-kind support to continue the research on the International Space Station.



Bristol-Myers Squibb investigation in the Commercial Generic Bioprocessing Apparatus: Antibiotic Production Enhancement (ground control on the left and flight sample on the right)

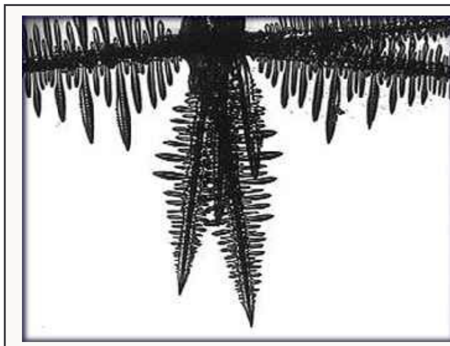
Gene Expression in Microgravity: Our spaceflight research demonstrated that microgravity significantly changes gene expression in cultured cells and whole animals. This type of research may point the way to identifying the specific genes and gene products associated both with bone loss and muscle atrophy in space and with diseases on Earth such as osteoporosis and muscle wasting. More than 1,600 of 10,000 genes showed a change in the space-flown cells. Investigators are now beginning to hone in on groups of specific genes affected by microgravity. Cultured fibroblast cells showed



The response of human cells to microgravity is fundamental to the adaptation of terrestrial life to low gravity environments and is reflected in the genes that are activated in space. As the changes in cells in microgravity are observed, new opportunities in understanding the fundamental processes in cells are revealed. This sequence of images shows the difference in gene expression between microgravity, a 3-g centrifuge and in a rotation wall vessel (bioreactor).

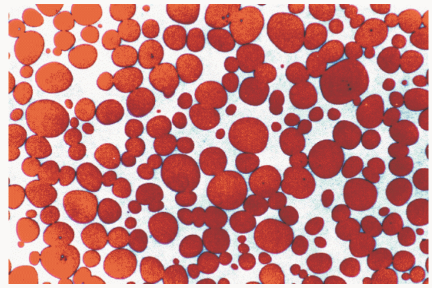
changes in 10 genes, most of which are involved in either the regulation of bone density or the development of inflammation. The effect of microgravity on gene expression was also examined in whole animals. The protein myosin is a basic building block of muscle, and one component of myosin has four different forms, each controlled by a different gene. A researcher showed that in rats exposed to microgravity, the ratio of the forms of myosin changes, resulting in less of the type of muscle that is associated with maintenance of posture against gravity.

Fundamental Solidification: Three Shuttle flights of the Isothermal Dendritic Growth Experiment (Professor Martin E. Glicksman, Rensselaer Polytechnic Institute) yielded internationally recognized benchmark data that enabled the first complete validation of the basic heat transfer model of dendrite growth. Understanding the evolution of single, isolated dendrites is a critical first step in being able to predict and control the industrial process of metal casting. The performance of most structural alloys is strongly influenced by the way that solid metal is formed when hot liquid metal is allowed to cool. Solidification commonly begins when many tiny metal snowflake-like dendrites form and subsequently evolve. How these dendrites begin and grow is of interest not only to the casting industry, but also to scientists and mathematicians who study pattern formation, non-equilibrium physics, and computational condensed matter physics.



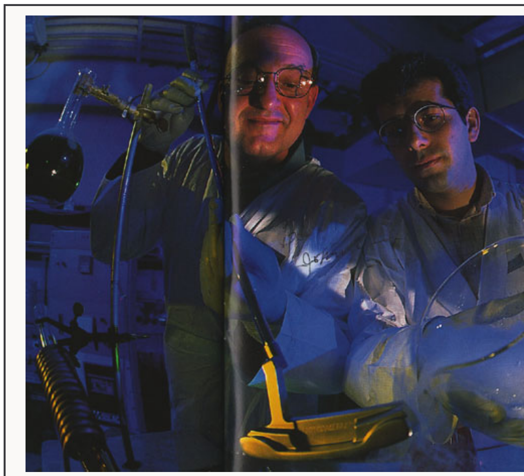
Dendrites grown in space in the Isothermal Dendritic Growth Experiment

Liquid-Phase Sintering: OBPR's Shuttle experiments on the 'Gravitational Role in Liquid-Phase Sintering' (Randall German, The Pennsylvania State University) were used by Kennametal, the market leader in North America in metal-cutting tools and second worldwide, to enable their products to be manufactured to shape without expensive post-sintering machining operation. Sintering is an industrial process that accounted for $3 Billion of the U.S. economy in 1999. About 80% of that market relies on liquid-phase sintering, a thermal treatment that bonds powders together through compaction and heating to make a finished product. Surprisingly, many of the spaceflight samples distorted more than the samples processed on Earth. Components in microgravity often went through an early stage where they had near zero strength. This strength loss allowed weak forces like surface tension to distort the compact. Since the absence of gravity actually weakened the materials, an unanticipated result, materials' scientists learned of the need to rewrite theory for sintering and gravity effects on distortion. An interesting post-flight addendum: Kennametal hired Dr. Yixiong Liu, a postdoctoral associate of the research group at Penn State, and subsequently selected Dr. Liu for their Millennium Award for Technical Excellence.



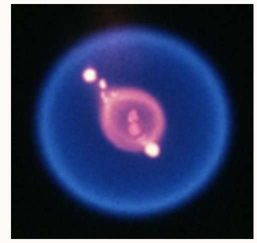
Liquid Phase Sintering Micrograph: Resulting grain size and distribution in 83 weight percent after 120 min gravity

Thermophysical Properties: Containerless processing in space using levitation technology determined important thermophysical properties of glass-forming metallic alloys (Professor William Johnson, California Institute of Technology). As a result of these measurements that were not possible on the ground, and parallel research funded by other agencies, metallic glass alloys were produced that are very strong yet able to be distorted (by impact) and still fully recover shape and energy input. This means that if this metallic glass serves as the face of a golf club that is distorted by the ball at impact, the club later releases all of the energy that was initially needed to distort the club face, and should enable the ball to go farther. Such clubs are now on the market. Metallic glass was subsequently used by NASA's Project Genesis to capture the solar wind. A similar type of metallic glass may be deployed by the Department of Defense for armor penetrators in artillery shells, eliminating the hazard of and need for depleted uranium that presently is used.



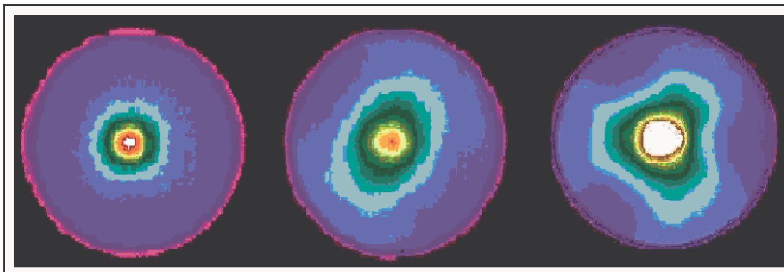
A commercially available golf club resulting from this research. The copper levitation coil in the lower left was actually used in the development of bulk metallic glasses (Credit Sports Illustrated).

Droplet Combustion Experiments: From droplet combustion experiments on the Shuttle, new reaction rate parameters for selected fuels were established or validated, and most importantly, transitioned into practice: the two U. S. aircraft engine manufacturers used these results to improve their chemical kinetic models via validated reaction rate parameters. Isolated droplet combustion provides an irreplaceable, classical one-dimensional test bed for validation of theories and numerical predictions that appear in textbooks for the last 40 years.



A perfectly round burning droplet in space.

Oscillatory Thermocapillary Flow: The Surface-Tension Driven Convection flight experiments conducted by Simon Ostrach and Yasuhiro Kamotani from Case Western Reserve University provided the first-ever validation of models of steady and oscillatory thermocapillary flows over an extended range of conditions. Prior to these experiments, these flows (driven by surface-tension gradients induced by temperature variations along the free surface of a liquid), had received very little attention because they are often overwhelmed by buoyancy-driven motion on Earth. The tests proved that the non-dimensional parameter known as the Marangoni number is not sufficient to indicate the onset of oscillatory flow. On the other hand, the experiments demonstrated that surface deflection plays a key role, as the flow became oscillatory when a non-dimensional parameter associated with surface deflection exceeded a critical value. These flight experiments led to a rapid expansion in thermocapillary flow research, which is applicable to numerous technologies, such as crystal growth, liquid positioning in MEMS devices, and microchip thermocapillary pumps for DNA analysis. The flight project also yielded 17 archival journal publications, 24 invited talks, 6 Ph.D. dissertations, and 5 Master's theses.

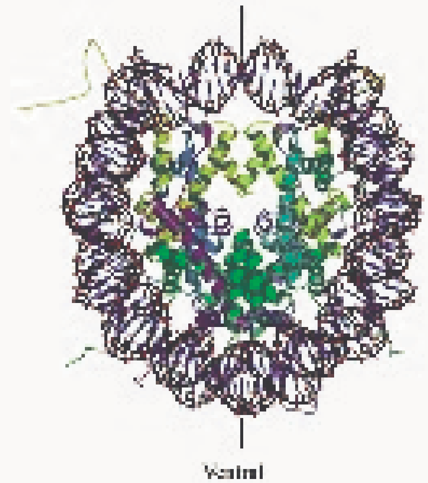


Various infrared images, showing the liquid pool's surface temperature distributions, of oscillatory thermocapillary flow observed during STDCE experiments.

Advanced Human Support Technologies: The first closed chamber test integrating bio-regenerative and physical-chemical life support technologies with a 'human-in-the-loop' provided unexpected health and safety benefits for Shuttle and ISS crews. This test was one of a series of closed chamber tests to validate emerging life support technologies. Detection of an anomalous reading in crew thyroid activity resulted in an immediate change in Shuttle protocols for water consumption and, in another instance, a potentially serious problem with formaldehyde off-gassing resulted in a change in planned ISS

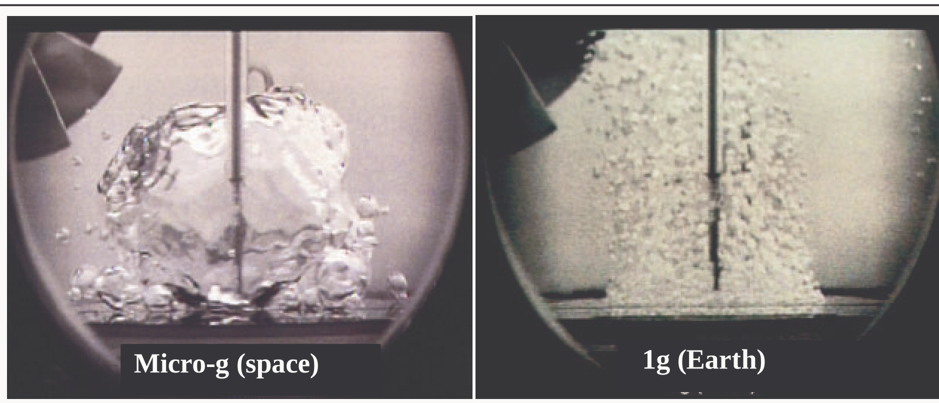
acoustic insulation materials. These tests demonstrated the value of ground-based testing for subsystem integration and validation and the resolution of problems that otherwise may have to be accomplished on orbit.

Structural Biology: A key building block in the packaging of DNA in humans and other higher life forms, and in the regulation of gene expression, is now significantly better understood because of the analysis of protein crystals grown in space. Research groups at the Oak Ridge National Laboratory and the Indiana University School of Medicine used the microgravity environment of space to grow crystals and determined the best published structure of the entire nucleosome core particle. This new structure revealed important ion binding sites that may help explain arsenic's toxicity.



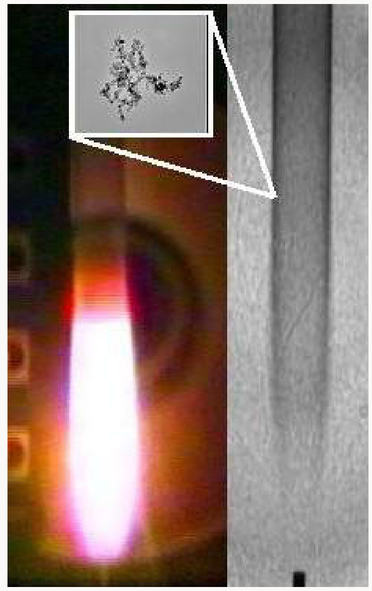
Most detailed structure of Nucleosome Core Particle, 2.5 Å, shows asymmetry and key ion binding sites linking the structure: 40% more data from space than has been obtained on Earth.

Boiling Phenomena: Results from a series of Shuttle experiments on boiling liquids are being used by an electronics company to design advanced cooling methods for electronic boards for use on earth and in space. The experiments revealed the possibility for quasi-steady nucleate pool boiling in long-term microgravity, making it a potentially useful technique to save mass in thermal control systems in spacecraft. The microgravity tests showed an enhancement of about 30% in heat transfer, but there was a significant decrease in the critical heat flux (CHF), a parameter that sets the upper limit for safe operation of equipment.



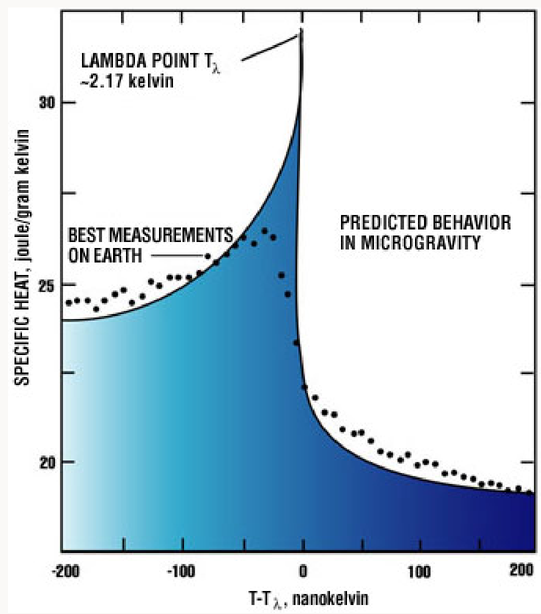
Micro-g and normal gravity images of boiling show a clear difference in bubble size. On Earth, small bubbles rise away from heated surfaces due to buoyancy.

Soot Production: A universal relationship between sooting processes and degree of mixing in diffusion flames was identified under microgravity conditions provided by spaceflight. This research is motivated by and has application to several important problems, as follows: the large public health hazard caused by combustion-generated soot; the loss of life caused by the inhalation of toxic carbon monoxide that is intrinsically associated with the presence of soot in unwanted fires; the loss of property due to the spread of unwanted fires that is caused by radiation from hot glowing soot particles; the potential limitations to the manufacture and use of Diesel engines, jet engines for aircraft and furnaces due to problems of soot emissions; and developing new methods for producing and exploiting carbon black for industrial products.



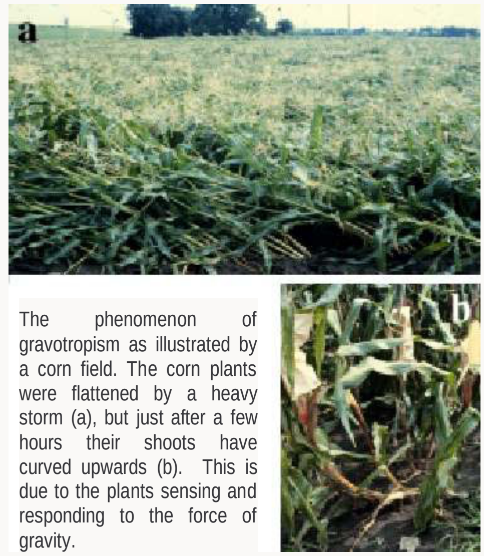
The visible flame from the Laminar Soot Processes experiment on the Shuttle (shown on the left) has an open tip through which small soot particles issue. The soot is made visible by a laser light sheet. The soot stream is then sampled so that the size of the primary and aggregated soot particles were found.

Critical Fluids Phenomena: The renowned phase transition theory was verified ten times more precisely than ever before in the first space-based low-temperature physics experiment. In 1982 Kenneth Wilson received the Nobel Prize for his theory of critical phenomena, which is useful to understand everything from magnetism to weather modeling, earthquake predictions and cosmology. Testing Wilson's predictions for helium was the prime goal of the Shuttle-based Lambda Point Experiment (LPE), a study of low temperature critical phenomena. LPE was a high-resolution investigation of the phase transition that occurs when ordinary liquid helium becomes a superfluid. LPE performed heat capacity measurements with a stunning temperature resolution of approximately one nano-Kelvin, enabling the most stringent test of phase transition theory to date.



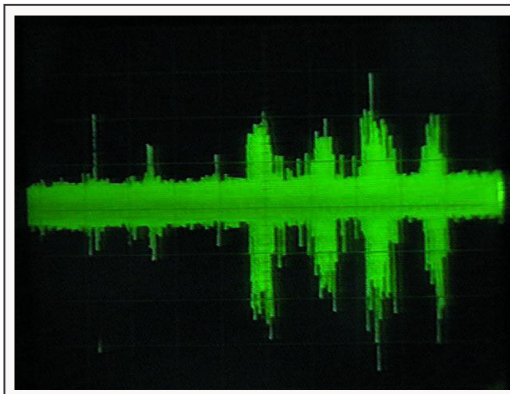
This graph illustrates the predicted curve of helium's specific heat around the temperature at which it changes from a liquid to a superfluid. The lambda point, so called because the curve resembles the Greek letter "λ," is located at approximately 2.17 kelvin. Measurements of helium in this realm on Earth are inaccurate due to pressure gradients in the sample material.

Plant Response to Gravity: The mechanisms that regulate plant responses to gravity were identified in spaceflight. One of the oldest questions in plant physiology is how plants respond to gravity—roots bending towards gravity and shoots away from it in a phenomenon called gravitropism. Evidence for the idea that starch grains are the actual plant gravity sensors was found in Shuttle experiments with plants containing different amounts of starch. More specifically, the genes *ARG1* and *AGR1* were identified as playing a role in transmission of the gravity-sensing signal from the site of sensing to the site of the growth response. *AGR1* is involved in transport within plants of auxin, a plant hormone that appears to be part of the gravity-sensing signal. The role of gravity in plant development is also of interest since numerous earlier attempts at plant reproduction in space failed. A researcher showed that the failures were likely due to deficiencies in providing a suitable growth environment in space, and were not a direct effect of microgravity. Plants grown in space in a specially designed, well-ventilated growth chamber successfully underwent a complete life cycle, producing viable seeds, which demonstrated that gravity is not absolutely essential for plants to reproduce and to undergo a complete life cycle.



The phenomenon of gravotropism as illustrated by a corn field. The corn plants were flattened by a heavy storm (a), but just after a few hours their shoots have curved upwards (b). This is due to the plants sensing and responding to the force of gravity.

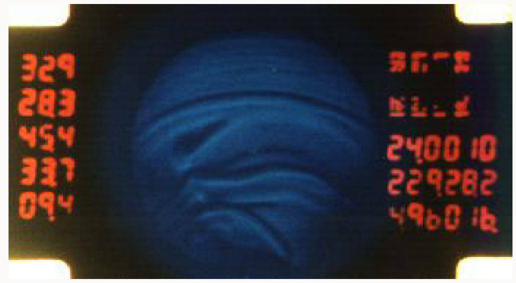
Neuroplasticity: The ability of the brain and nervous system to adapt to changes in the environment – Neuroplasticity -- research in space demonstrated that microgravity leads to significant changes in the number and shape of synapses (nerve connections) in developing rat brains, while another found distinct anatomical changes in a part of the brain that receives significant input from the vestibular system (the gravity perception system in animals). Experiments conducted on several Shuttle flights showed that the synapses of nerve cells directly involved in perceiving gravity in the vestibular system are altered in number and shape and that the circuitry of these cells is changed. Vestibular nerve cells of fish flown on Neurolab exhibited a large increase in responsiveness to a gravitational stimulus soon after they returned to Earth, but this effect disappeared after about a day, as the animals readapted to Earth's gravity. These findings that certain nerve cells are "plastic" with respect to changes in gravity are not only adding to our understanding of the phenomenon of neuroplasticity, they also provide hints for new



Sympathetic nerve activity: muscle sympathetic nerve activity of autonomic nerves during and after spaceflight was measured in astronauts during the Neurolab mission.

approaches to rehabilitative training and/or pharmacological treatments for vestibular and balance diseases.

Understanding Planetary Atmospheres: Planetary atmospheres were studied in small-scale by Shuttle experiments using electrostatic forces to warp gravity into a radial vector field, centrally directed toward the center of the cell. These allowed visualization of thermal convection in a spherical shell of liquid subject to rotation and differential heating, as in planetary atmospheres and stars. The objective is to categorize convective patterns that can occur in highly nonlinear and turbulent flows. The observed unique, unpredicted convective patterns provide an alternative view of the mechanisms for “banded-looking” structures in planetary atmospheres like Jupiter. Also, “climates” can persist or stay “locked” even though external conditions change slowly. The results of this study were published as a cover story in Science.



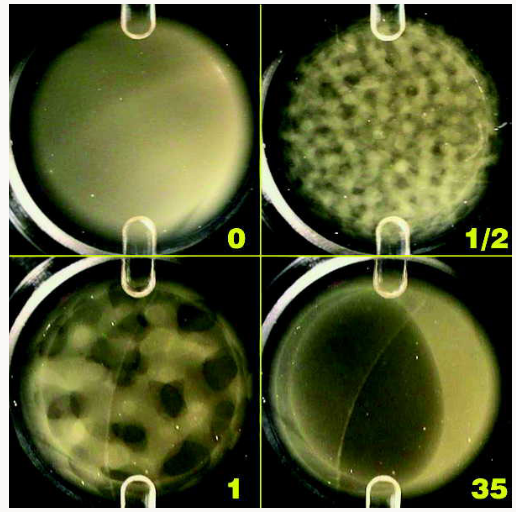
This enlarged movie frame from the fluid flows inside the Geophysical Fluid Flow Cell shows flow patterns as revealed by density changes in the oil inside the "planet in a test tube" — the Geophysical Fluid Flow Cell. The numbers on each side show the experiment conditions. The experiment took advantage of the microgravity environment -- the weightless conditions inside the orbiting Space Shuttle — and was flown in 1985 and 1995.

World-Record Crop Yield: Remarkably high yields of crops were achieved in NASA-funded controlled environments using high intensity lighting, elevated CO2 concentrations, and hydroponic culture. This includes wheat yields of 900+ bushels/acre that were 4-5 times those of world record field yields (approximately 200 bushels/acre) by Bugbee and colleagues at Utah State University, and yields with potato that were nearly two times world records by Tibbitts and colleagues at the University of Wisconsin. These findings indicate there is still room to improve yields of many field crops.

The world record for wheat in the field is 230 bushels per acre. This is 1.54 kg per square meter. NASA’s highest wheat yield, published in Plant Physiology (1988) was 60 g per square meter per day. Much higher light levels than in the field and hydroponic culture were used to produce this result. Elevated CO_2 was responsible for about 40% of the yield increase.

From the early research on the International Space Station

Physics of Colloids in Space: David Weitz, Harvard University; A range of colloidal samples were flown and achieved many unpredicted and novel results with potential applications to next-generation computers and communication technologies, materials for novel drug delivery, and industrial product improvements. Colloids are solid-liquid mixtures that may behave like pure liquids, gels, or crystals, depending on the volume fraction (a function of the number and sizes of particles) of the small solid particles in the liquid. An unpredicted, spontaneous de-mixing (phase separation) process was discovered in colloidal-polymer mixtures: regions that were colloid-rich and colloid-poor evolved after long durations on orbit. Also the extended time and low gravity of the ISS revealed that binary colloids will crystallize under conditions that would never crystallize on Earth. It was therefore demonstrated unambiguously that gravity plays an important role in the ultimate size and morphology of the crystals. For the first time, a silica gel was formed under low volume fraction. The scientific findings add to fundamental knowledge in colloid and condensed matter physics regarding the nature of transitions among gaseous, liquid, solid/ crystal, and glassy states of matter.



Space provides the rate opportunity to study colloids as they naturally separate without the effects of buoyancy. This 35 day run on the ISS is shows a colloidal system in the phase separation process - which was observed to completion on the ISS, not possible on Earth.

Sub-Regional Assessment of Bone Loss in the Axial Skeleton in Long-Term Spaceflight: Thomas F. Lang, University of California, San Francisco; The objective of this study is to determine the distribution of bone loss in the spine and hip in long-duration spaceflight and to assess how bone is recovered after return. At this point, complete baseline data have been acquired for 11 ISS subjects, and a total of five subjects have now had follow-up visits. The mean bone loss at the spine, while statistically significant for the group (paired T-test), is quite small and would be barely detectable in an individual outside of the precision error of the technique. There is a trend for the vertebral regions containing cortical bone to show larger losses than the trabecular regions. The observed mean bone loss at the hip is two- to threefold larger, with a trend towards larger changes in the trabecular than in the cortical compartments. From this study, we obtain a better understanding of post-flight fracture risk.


Resistive exercise is currently used to fight bone and muscle loss for Shuttle and ISS crews.

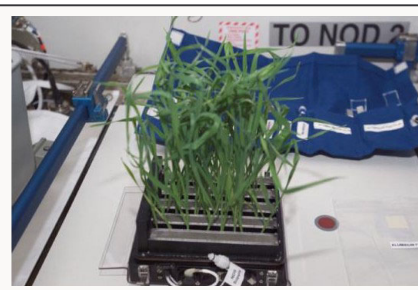
Advanced Astroculture: The Wisconsin Center for Space Automation and Robotics Apparatus successfully grew two generations of Arabidopsis thaliana. Plants were grown using seeds harvested during earlier ISS operations. This multi-generational research capability is a clear example of the benefits of longer duration microgravity than was possible during Shuttle missions. This initial development of multi-generational growth of a non-food crop paves the way for multi-generational research including gene expression, and the development of a variety of food crops and improved crop development.

Healthy soybean plants grow under wide-spectrum light-emitting diodes (LEDs) inside an ADVASC growth chamber on June 28, 2002. Video feed allows the researchers to track the plants' daily progress. Using this video and photos provided by the Station crew, the researchers decide when the plants should be pollinated, harvested, and dried out.

Macromolecular Crystallization: Craig Kundrot, NASA Marshall Space Flight Center; Thaumatin crystals diffracted to higher resolution than any crystals ever grown on the ground. The ISS-grown crystals provided over 50% more diffraction data as the best ground-grown crystals. Thaumatin is a protein isolated from a West African plant. It is 2,000 to 3,000 times as sweet as sucrose (sugar) and is approved as a sweetener or flavor enhancer in Japan, the EU and the US. Obtaining improved crystals on two separate experiments on ISS demonstrated reproducibility. Detailed understanding of the atomic structure may aid the development of artificial sweeteners.

Crystals photographed under a microscope, grown during STS-106 in the EGN Dewar. The solution that grew these crystals and others were prepared by students.

Photosynthesis and Metabolism of Super Dwarf Wheat in Microgravity: Gary Stutte, Dynamac Corp.; The International Space Station provided the research laboratory environment necessary to obtain the most scientifically credible data set on photosynthesis and transpiration of higher plants ever obtained from space. From these model system data, the effects of microgravity on metabolism and processes associated with photosynthesis begin to be known, and we can more confidently develop reliable plant-based atmospheric regenerative systems targeted for long-duration exploration. Examples of impacts of this

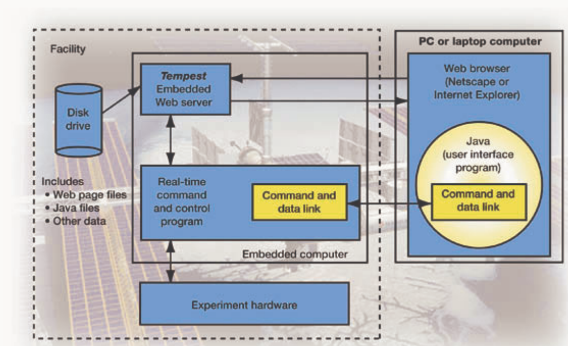


Initial assessment of the data indicates that there was no difference in growth rate or dry mass of wheat grown on the ISS. In addition, there was no difference in daily photosynthesis rates, leaf responses to canopy CO_2 concentration, or light intensity. In other words, there was no effect of microgravity on stand level photosynthesis or transpiration rates of developing wheat.

research for Earth benefit include: 1. Improved growth media for horticultural production of plants. Extensive testing of technology pioneered at NASA, zeolite as a growth media, was conducted for the PESTO experiment, leading to commercialization of a zeolite-based product, ZeoPro, which ZeoponiX, Inc. is currently marketing to the greenhouse and turf industries. 2. Miniature soil moisture and oxygen sensors for monitoring soil conditions. After PESTO evaluation tests, commercial companies are developing these more accurate and precise sensors for application to the greenhouse industry. 3. Improved environmental control techniques for plant growth. The techniques have been adapted to soil physics research within USDA, greenhouse control of CO_2 in private industry, and lighting systems in academia. 4. Modeling impacts of global climate change. Models for transpiration and photosynthesis developed for the PESTO flight experiment were used to determine effects of global climate change on water use and carbon balance in the Florida Upland Scrub habitat. 5. Education of students: “Farming in Space”, the educational outreach activity developed on the objectives of the PESTO experiment, has reached tens of thousands of school children through classroom exercises, webcasts, and webchats.

Innovations In Technology

While scientific ventures were the centerpiece of our history, many innovative technologies were developed that are of special benefit to the space program and to society and industry. Here are a few examples:



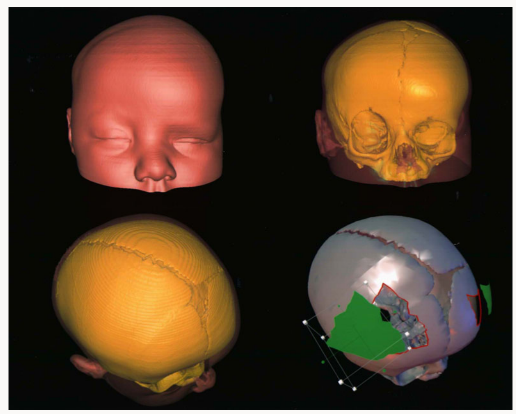
Tempest is enabling software. It enables data and expertise for next generation system design for low-g; synthesis and life support technologies and subsystems that are light, validation of life support technologies in relevant environments; basic research in areas of air revitalization, water recovery, food production and processing, and solid waste processing; Integrated testing of subsystems; Multi-phase transport and flows modeling and experiments; significantly reduces software lifecycle time and produces high quality, up-to-date applications.

Embedded Web Technology (EWT)/Tempest: Developed to support our ISS facilities in combustion and fluids, our EWT program called Tempest won the following awards: NASA Software of the Year in 1998, a 1999 R&D 100 Award (The R&D 100 Awards recognize the "100 most technologically significant new products and processes of the year. The Chicago Tribune calls these awards 'The Oscars of Invention'), and a 2000 Award for Excellence in Technology Transfer from the Federal Laboratory Consortium (a consortium of over 600 federal laboratories) for Technology Transfer. EWT is the application of software developed for the World Wide Web to embedded systems. Embedded systems contain computers, software, input sensors and output actuators, all of which are dedicated to the control of a specific device. Examples of devices with embedded systems include cars, household appliances, industrial machinery, and NASA Space Experiments. EWT allows a user with a computer and Web browser to monitor and/or control a remote device with an embedded system over the Internet using a convenient, graphical user interface. The embedded processor market itself is expected to be larger than the desktop market and to grow to over $100 billion in the next decade.

Bioreactors: Our cellular biotechnology work has yielded more than 25 patents and disclosures, and over 6000 Bioreactors today are in use in the US. Licenses have been issued to manufacture bioreactors for use in universities and industries, for the production of pancreatic islets cells for transplantation into patients with Type I diabetes, and to use the bioreactor to promote the growth and differentiation of human cells for transplantation.

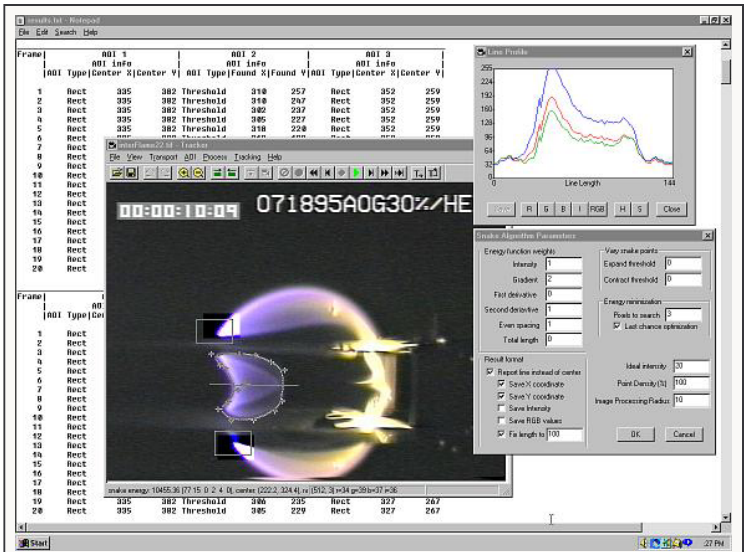
A Synthecon low aspect ratio Bioreactor.

Surgical Software: Developed by a NASA PI to facilitate the visualization of a portion of the body's balance organ in the inner ear, the software is now being used by surgeons to provide 3-D reconstructions of patient defects and projected repair during surgical planning. This potential software won NASA's Software of the Year award, and is being used in hospitals around the country to aid surgeons in planning operations. Using this software, the surgeon can re-create the individual's 3D anatomy from the 2D medical images, develop a computer-generated model, and evaluate through simulation alternative surgical outcomes to benefit the patient. The first testbed for the software application was by a NASA Ames-Stanford team that applied the virtual reality computer tools to aid in complex facial reconstructive surgery. Shown in the figure, surgeons create a 3-D image to manipulate and plan surgical procedures. As an outgrowth the team is focusing now on applying similar virtual reality computer and simulation tools to promote life sciences applications, such as development of complex procedures in an ISS glovebox, interactive procedural training incorporating problem solving scenarios, enhanced interactions between the principal investigator and the astronaut using distributed internet connections, teleoperations, and more complex human-computer interactions such as manipulation and surgery of soft and hard tissues.



A `software scalpel' used with clear, accurate three-dimensional (3-D) images made from a series of scans of the human head will help doctors practice reconstructive surgery and better predict the outcome.

Protein Crystal Growth: NASA, X-Ray Optical Systems, and other collaborators worked to develop the world's most compact intense source of commercial X-rays for potential use on the ISS. Other technological advances have led to the award of at least 14 patents. The new x-ray optics could identify and determine the structure of proteins four to 10 times faster than conventional methods. Among industrial applications, the optics are enabling the cost-effective development and monitoring of magnetic data-storage materials by IBM Corp., which reports four- to 16-fold increases in X-ray output. The applications still at the research stage include defect composition analysis for semiconductor manufacturing, X-ray lithography of high-density computer chips and digital mammography, where early tests produced exceptional image clarity. In general, the spaceflight program has produced the most accurate and detailed three-dimensional, atomic structures of about 40 proteins, DNAs, and viruses. These include the most detailed structure of a virus and a structure of insulin binding a drug that could not be seen in ground-based research. The program has aided Structural Genomics, a follow on to the Human Genome Project, by pioneering the development of two crystallization systems that help overcome the greatest bottleneck in Structural Genomics: crystallization.

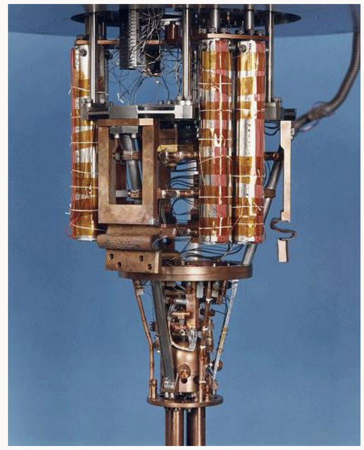


Tracker analyzing the flame front of interacting flames. Showing the snake (active contours) options dialog box and an interactive line profile tool.

Tracker: Like Tempest, this program won an R&D 100 award. Employed successfully by over 30 microgravity investigations and by General Motors R&D Center, Engine Research Department (through a Space Act Agreement), Tracker is a computer program that allows sophisticated object tracking and processing needed in the analysis of experimental images. Tracker replaces tedium and human error by automating the process of examining each video frame and processing each image to reveal the desired details of the objects of interest. For example, Tracker automates the analysis of an object's physical parameters such as position, velocity, acceleration, size, shape, intensity characteristics, color, centroid, as well as a number of other measurements. Tracker has followed objects such as flames, bubbles, droplets, blood cells, and even migrating fish.

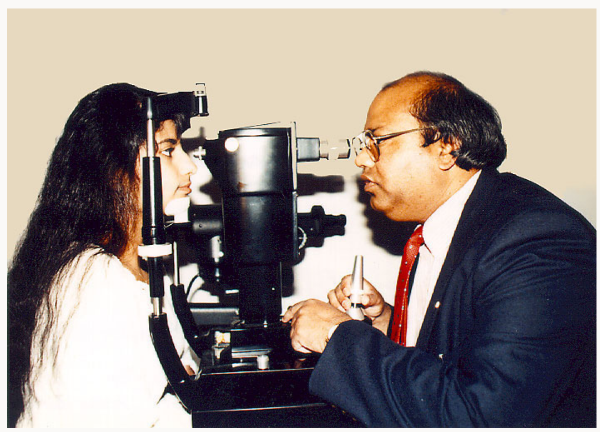
Lighting Tool: NASA has developed a tool that uses luminance images as an improvement to training scenarios where lighting can be a factor in performance. This training tool allows accurate prediction of difficult or limiting lighting situations that can make robotic remote manipulation dangerous or cause unnecessary and costly delays in EVA activities. Testing revealed that subjects who trained with shadowing in their simulation perform the real task faster and more accurately. This technology has been used successfully on several ISS assembly flights.

High-Resolution Thermometers: The development of high-resolution thermometers in NASA's Fundamental Physics research program, first by the Stanford group of Dr. John Lipa and subsequently by other groups in the discipline, made it possible to make quantitative measurements of intrinsic temperature fluctuations in macroscopic objects. This new capability is relevant to fundamental issues in statistical mechanics, and made it possible to improve the design to obtain even higher-resolution thermometers for future flights. The technology was distributed in the low temperature community, allowing many laboratories to improve their thermometry on the ground.



The calorimeter in the Lambda Point E was contained inside a thermal control system (the upside-down conical section) to regulate and stabilize its low temperature. The partially viewable copper tubes at the bottom of the structure are high-resolution thermometers, which were used to measure the temperature of the helium to the nearest nanokelvin.

Laser Light Scattering and Cataracts: A laser light scattering technique to observe particle sizes and concentrations in fluid physics' spaceflight experiments has been adapted by Dr. Rafat Ansari and associates of NASA Glenn Research Center to detect signs of cataract growth in humans years before the cataracts became visible by conventional methods. The cataract detection device went into clinical testing at the National Eye Institute/National Institutes of Health in 1999. Early detection allows assessment of preventative drug therapies and may help mitigate the health care costs of cataracts, which affect nearly fifty million people annually. The laser light scattering technique is currently being adapted for other clinical purposes such as to identify people with diabetes or Alzheimer's disease via a non-invasive measurement. In addition, it is being used on the ISS in fluid physics' experiments involving colloidal systems.

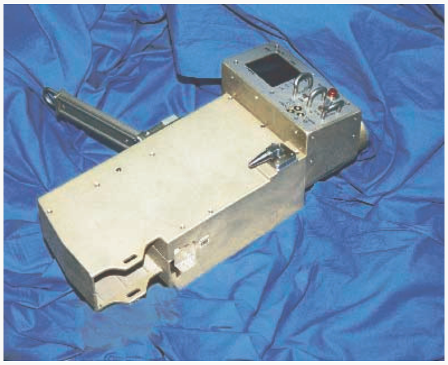


Dr. Rafat Ansari (right) and his daughter, Rahila Ansari, demonstrate how the probe could be incorporated in a standard ophthalmologist's examining apparatus.

Nutrient Film Technique for Crops: NASA was the first to demonstrate *on a production scale* the concept of nutrient film technique (NFT) hydroponics to produce potato tubers. This approach is becoming popular for the production of "seed" potatoes to propagate disease-free planting stock. Several potato seed growers as well as large corporations (e.g., Frito Lay) are using hydroponic production techniques developed by NASA for producing seed potatoes.

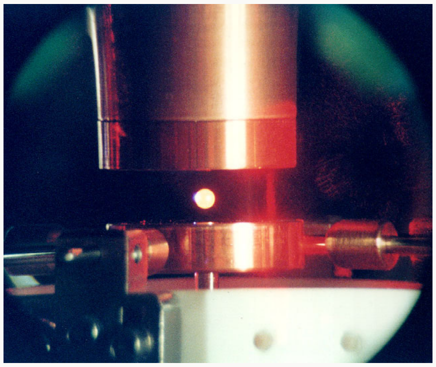
The NFT system contained separate sloping rectangular plastic troughs. Each trough contained 3 plants spaced to give an effective planting density. Recirculating solution flowed through the troughs to give a steady stream or film of nutrient solution to the plant roots.

World's Smallest Mass Spectrometer: A quadrapole mini-mass spectrometer was developed by the NASA Jet Propulsion Laboratory and incorporated into a trace gas analyzer (TGA) instrument designed to detect extremely small amounts of toxic chemicals, such as hydrazine, that might be encountered during an EVA outside of the ISS. The TGA flew on STS-105 in February 2000 and remained in the ISS airlock for nearly two years. A re-furbished unit is also now on the ISS. This technology has the potential to replace the some functions of the baseline ISS monitoring technologies and has many Earth-based applications in anti-terrorism activities and environmental monitoring. The JPL team that developed the mini-mass spec has recently been approached by Consolidated Edison to modify this technology to develop a field device to detect poly-chlorinated biphenyls.



The Trace Gas Analyzer is a miniature spectrometer unit weighting about 5 pounds and roughly the size and shape of a small shoe box. Astronauts carry the device on a chest pack, where it can easily be pointed towards areas being inspected. A small screen displays a graph that reports the detection of specific gases and their amounts, which presence indicates a potential safety risk.

Containerless Experimentation Technology: Initially created to take advantage of the unique low-gravity environment of space, our unique technologies have been implemented in Earth-based laboratories across the world to manipulate solid, liquid, and composite samples at very low, ambient, and very high temperature in the absence of containers. A particularly useful experimental technique is a high-temperature electrostatic levitator, which creates the capability to levitate, melt, and solidify a wide variety of high-purity refractory metallic materials under high vacuum. The equipment permits the making of measurements



A metal droplet levitated inside the Electrostatic Levitator.

of such thermophysical properties as viscosity, specific heat, surface tension, and density. This technique is being implemented by government and private sector research laboratories in the United States and Europe to address a variety of industrial needs for the detailed knowledge of the properties of these materials during manufacturing.

Educational Outreach and Public Outreach

Examples of our most recent efforts to reach diverse communities and embolden and inspire a new generation of scientists and engineers are as follows:

- The National Air and Space Museum displays our acceleration measurement system, which has the honor as the U.S. equipment with the longest stay (about 45 months) on the MIR space station as part of the NASA-MIR program. Our equipment is housed in the new Space wing at Dulles International Airport, along with the Enterprise, a Spacelab module, and other space items.
- Nearly 1,000,000 students around the world engaged in a plant space biology investigation simulation conducted coincidentally with the same experiment on the Shuttle mission STS-87. In the first collaboration in space between the United States and Ukraine, over 4,500 teachers in the U.S. and 500 in Ukraine trained to use the NASA's teacher's guide to instruct these students. The reach went far beyond these countries' borders as electronic media enabled dissemination of the teacher's guide throughout the world.
- In 2000, our science and mathematics posters, teacher's guides, mathematics briefs, microgravity demonstrator manuals, microgravity technology guide, microgravity mission and science lithographs, and World Wide Web microgravity resources sheets were distributed at conferences attended by more than 50,000 elementary and secondary school teachers and administrators.
- The Challenge Project, an outreach precursor to Shuttle Mission STS-95, the flight that returned John Glenn to space, blended the ideas of challenges, physical fitness, lifelong learning, and space exploration in unique experiential opportunities for inter-generational audiences. More than 283,000 people tuned in to the live Internet broadcasts. Public Service Announcements, A Wellness Seminar, and a variety of community events were hosted by collaborative partners that included the National Institute on Aging of the NIH,

Educators at the National Science Teachers Association (NSTA) annual conference take part in a workshop using an air track to simulate how mass is determined in a microgravity environment.

John Glen participates in an exercise activity during the STS-95 mission.

Garfield (Paws, Inc), the Muncie Group (Ball Foundation), The President's Council on Physical Fitness and Sports, American College of Sports Medicine, American Society for Gravitational and Space Biology, Sporting Goods Manufacturing Association, Space Transportation Association, Science Fiction TV, National Staff of YMCA Scuba Program. Film Director James Cameron; Edmund F. Ball, retired chairman/CEO of Ball Corporation; and Amanda Huser, a high school student from the Indiana School for the Deaf, were among the individuals whose life experiences personalized the Challenge Project themes and shared their stories and answered questions sent in by broadcast audiences. Affiliates of all major U.S. and U.K. television, radio, and print networks provided extensive coverage including special programming and exhibits in science centers and museums.

- High school students and educators from inner-city and rural schools and special needs and gifted and talented students as well as mainstream schools and home schooled students were directly involved in structural biology workshops, classroom and laboratory activities and the existing EGN structural biology ISS flight program. Selected students perform science activities and load flight samples, which are presented to them after the ISS mission. Partners include University of California; Alabama, Florida & Texas Space Grant Consortiums; Space Is Special Foundation; Parent Teacher Associations; Bell South; Telephone Pioneers; Lockheed Martin; United Space Alliance; Alabama A&M University; and Raytheon. An estimated 50,000+ students and 1090 teachers from 320 schools across 36 states and Puerto Rico have had direct involvement though workshops and classroom and laboratory activities. Over 420 students and 260 teachers from over 125 schools in 10 states have participated in the Flight Program (flight sample loading workshops & launch activities).

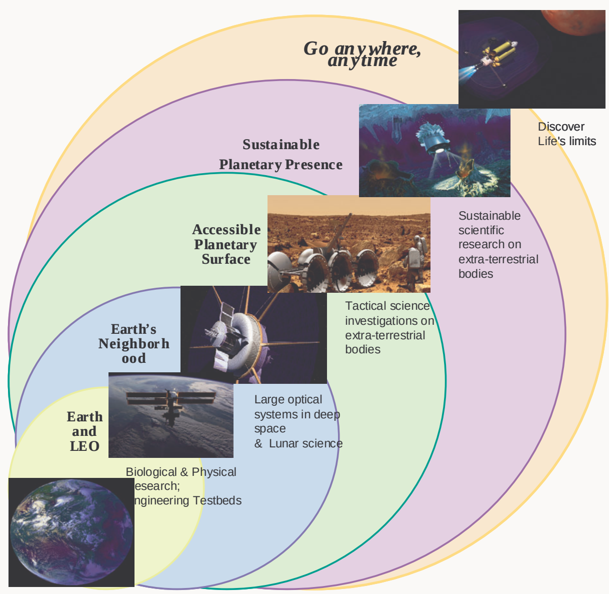
Visit the OBPR Website for information on the latest research findings and every experiment on the International Space Station: http:// SpaceResearch.nasa.gov

OUR CURRENT ORBIT -- AND BEYOND

NASA Administrator, Sean O'Keefe: "In broad terms, our mandate is to pioneer the future … to push the envelope … to do what has never been done before. An amazing charter indeed … NASA is what Americans … and the people of the world … think of when the conversation turns to the future.

"Pioneering the future is certainly something Abraham Lincoln would have understood,… I think it well that we follow his advice to "disdain the beaten path and seek regions hitherto unexplored." At NASA we indeed venture to regions unexplored and unknown.

"So in the end, NASA is about creating the future …"



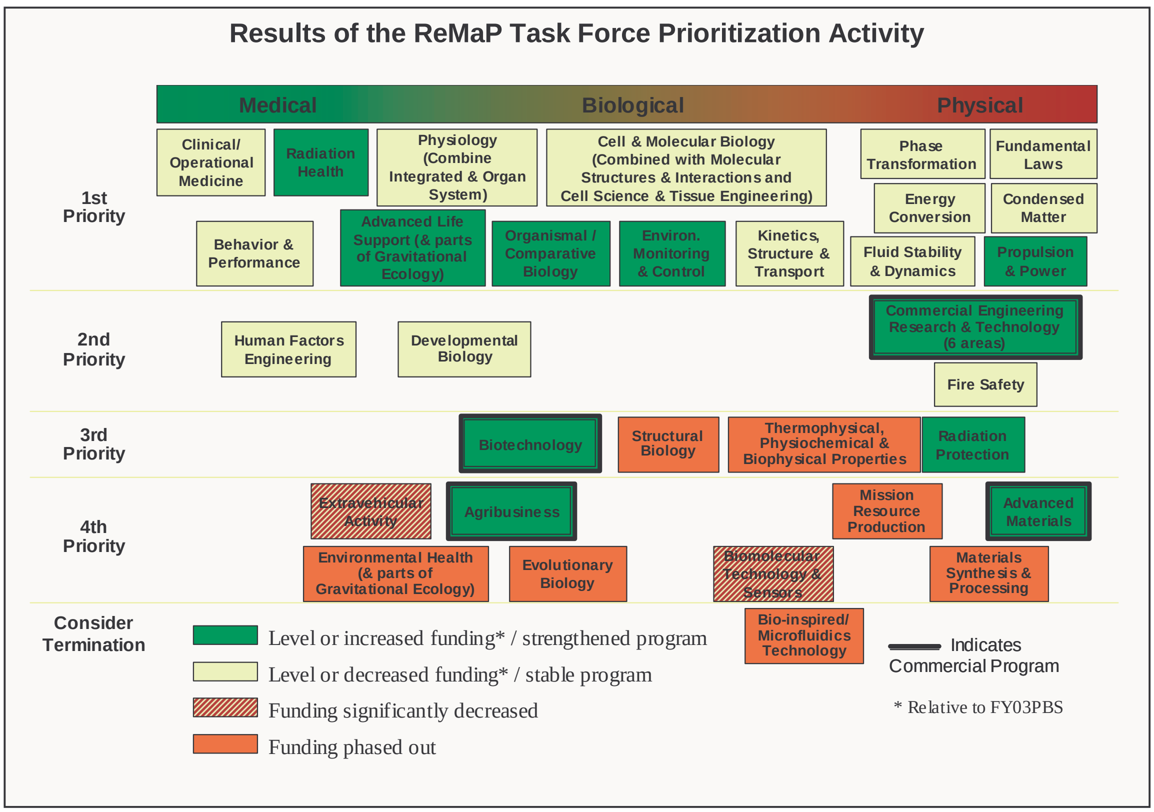
NASA Exploration Team's Stepping Stones Exploration Strategy.

Humans will extend the exploration of space. To prepare for and hasten the journey, OBPR must answer these questions through its research (on the ISS):

- **How can we assure survival of humans traveling far from earth?**
- **What must we know about how space changes life forms, so that humankind will flourish?**
- **What new opportunities can our research bring to expand understanding of the laws of nature and enrich lives on Earth?**
- **What technology must we create to enable the next explorers to go beyond where we have been?**
- **How can we educate and inspire the next generations to take the journey?**

Our Past Orbit was founded on fundamental and commercial research thrusts in a broad range of areas that are depicted below and which are described in Appendix A. Today, OBPR is intent on achieving a five-year research direction that is founded on the NASA Strategic Plan and the NASA Exploration Team's stepping stone's exploration strategy (see chart after O'Keefe quotation). Scientific purpose and technological enablers drive the exploration strategy.

The NASA Exploration team conceived a stepping stone strategy to exploring the universe, a strategy that is gaining widespread acceptance inside and outside the Agency. OBPR's research contributes directly to overcoming the identified hurdles that scientific exploration faces, as NASA moves away from low earth orbit. For the example mission to Mars, the NExT team's analysis suggests that nearly 8 times the launch mass of the ISS is needed using today's concepts and technologies. Necessary reductions requiring investments in new research and technology are also suggested for various subsystems. OBPR's targets for its research are identified in Red in this example. Accomplishing these reductions and overcoming the hurdles are not OBPR's responsibility alone, and will require a coordinated effort with the other NASA organizations.

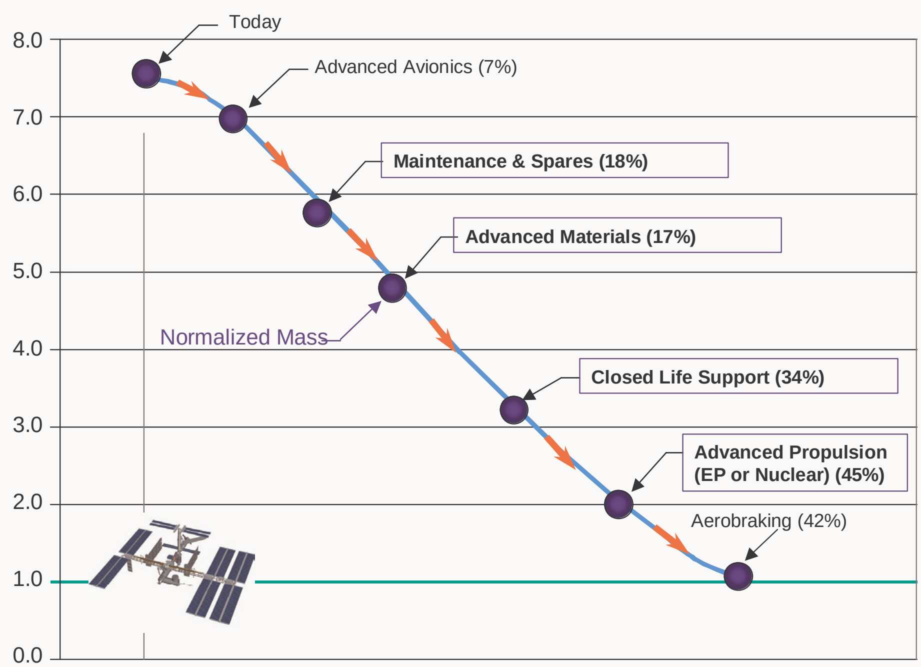


While the past demonstrated the merits of our research and validated the concept of an orbital laboratory, new areas of emphasis will carry OBPR beyond microgravity-based, curiosity-driven studies into a strategic research thrust that includes topics such as radiation health and protection, bioastronautics, and technology aimed at sustained human exploration of space. For humans to venture into and to explore space beyond where they have been, NASA must provide the same kind of safe environmental cocoon for space explorers that Earth provides for us, an environment with safe and renewable air, water, and food. NASA must provide a sufficient depth of understanding of how humans and other life forms adapt to the effects of space flight to be able to provide appropriate medical support tools to maintain human health. To enable this, and to ensure that we understand physical and biological processes in space well enough to exploit them safely, OBPR must provide an integrated research product that answers the key questions in our mission. The OBPR's sponsorship of research, therefore, is evolving to focus on answering these questions. Research roadmaps – both general and specific – will form the basis of time-phased competitive solicitations for research and technology and our research activities on the ISS.

An industrial advisory group noted recently, "It must be emphasized that each of the Organizing Questions 'enabling humans to extend the exploration of space' will also produce knowledge that improves life on Earth. For example,"

- "Telemedicine technology can be effectively used to assure the survival of humans traveling far from Earth and can be as effectively used to improve the medical services provided to remote and/or economically distressed areas on Earth."
- "Research on how space changes life forms, or more appropriately, life processes (even more appropriately, intermediary metabolism and organism ontogeny), can be used to support fundamental biological mechanism research ongoing in the terrestrial environment."
- "Technologies developed for sustaining regenerative life support systems for travel beyond LEO can be useful in protecting the Earth's environment. Recycling of consumables in space would likely have applications to improve terrestrial recycling activities or environmental remediation."

Evaluating technology investments for a human mission to Mars. The units on the ordinate are normalized by the mass of the ISS. The percentages shown in parentheses are target reductions in the mass of the associated system or flight element as compared to the original mass estimate based on today's technology. The circled items are ones that OBPR investigators will seek to impact.



This OBPR Research Plan is entirely consistent with the NASA 2003 Strategic Plan. The following table shows how the Organizing Questions relate to NASA's mission and goals.

NASA Mission	Associated NASA Goal	Associated OBPR Themes (As Defined In NASA Strategic Plan 2003)	Associated OBPR Organizing Question[1]
Understand and protect our home planet	3: Create a more secure world and improve the quality of life by investing in technologies and collaborating with other agencies, industry, and academia.	PRIMARY: Physical Sciences Research, Research Partnerships and Flight Support SUPPORTING: none	Primary: Q3, Q4 Secondary: Q1, Q2
Explore the universe and search for life	4: Explore the fundamental principles of physics, chemistry, and biology through research in the unique natural laboratory of space	PRIMARY: Physical Sciences Research, Biological Sciences Research SUPPORTING: none	Primary: Q3, Q2 Secondary: Q1
Inspire the next generation of explorers	6: Inspire and motivate students to pursue careers in science, technology, engineering, and mathematics.	PRIMARY: none SUPPORTING: Biological Sciences Research, Physical Sciences Research, Research Partnerships and Flight Support	Primary: Q5
	7: Engage the public in shaping and sharing the experience of exploration and discovery	PRIMARY: none SUPPORTING: Biological Sciences Research, Physical Sciences Research, Research Partnerships and Flight Support	Primary: Q5
Enabling Goals	Enabling Goal 9: Extend the duration and boundaries of human space flight to create new opportunities for exploration and discovery.	PRIMARY: Biological Sciences Research, Physical Sciences Research SUPPORTING: none	Primary: Q1, Q4 Secondary: Q2, Q3

[1] Shown are the primary and secondary purposes of the research that OBPR will sponsor to answer the OBPR Organizing Question.

Question 1: How can we assure survival of humans traveling far from earth?

OBPR Research Areas:
- Clinical/Operational Medicine
- Radiation Health
- Physiology
- Behavior & Performance

Quote:

ReMaP Task Force Report: "…the highest priorities should be based on research aimed at understanding and eliminating problems that may limit astronauts' health or function during prolonged space flight…research on the ISS is essential for evaluation of the long-term effects of the space environment and for flight testing of countermeasures."

Primary Outputs:

The establishment of clinical norms and acceptable levels of risk for human adaptation responses and probabilistic assessments of risks for long duration missions. The identification of the deleterious effects and the causal mechanisms resulting from long duration space habitation, and the; assessment and implementation of l effective countermeasure strategies to mitigate those effects. The development of health monitoring and assessment capabilities, effective crew screening and selection criteria, and best practices for in-flight medical contingencies, and post-flight rehabilitation. Crew certification for extended duration missions, including those beyond LEO, addressing radiation and other limiting factors (e.g., bone loss).

Desired Outcome:

A comprehensive strategy that maintains the health, safety performance of crews during and after space flight for missions of varying durations and ensures that the crew is not the limiting factor for long-duration human space exploration.

Note:

This research area is interdisciplinary, e.g.: F. Turek: "*Determining the fundamental biology behind gravity's effects on living organisms will surely lead to countermeasures for the adverse effects associated with microgravity.*"

Description:

Human space flight is inherently risky. Crew health drives the ability to maintain the International Space Station (ISS) and to perform experiments on the ISS and beyond. A key element of our strategic research thrust is specifically established to focus on applied biomedical and human support research to reduce the risks to crew health, safety and performance through development of effective countermeasures. This includes integrating science and medical research to generate the knowledge required to enable flight crews to leave Earth, and eventually LEO, perform their assigned tasks, and return to Earth with their health intact. This also includes sponsoring research to develop therapeutics, procedures, techniques, and equipment needed to address flight medical, safety, and performance issues.

To fully and robustly answer the question of assured human survival far from Earth, OBPR researchers must achieve two important goals:

1. Describe and understand human adaptation to the space environment and re-adaptation upon return to Earth
2. Use the knowledge so obtained to devise procedures that will improve the health, safety, comfort and performance of the astronauts

To ensure the most effective use of the OBPR's resources and to enable measured progress toward these goals, a Critical Path Roadmap (CPR) was developed as a key program planning tool focused on identifying space flight health, safety and performance risks and prioritizing the critical questions that researchers must answer to mitigate those risks associated with extended human spaceflight missions. The Bioastronatics Strategy (Jan., 2003) provides systematic identification, assessment, mitigation and management approaches to the critical risks, identified in the CPR, associated with the human subsystem of space flight.

Biomedical risks humans face in space:

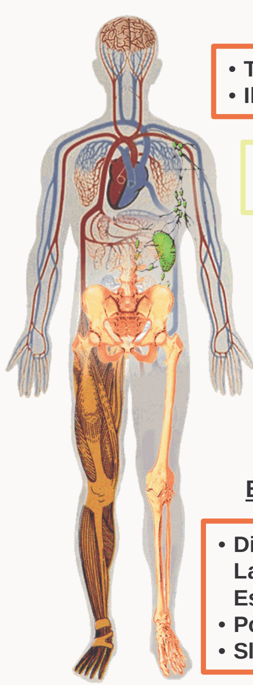
Effects of Radiation

- Carcinogenesis
- Synergistic effects with microgravity or environmental factors
- Late degenerative tissue effects

Physiological Changes

- Carcinogenesis due to immune system changes
- Occurrence of serious cardiac dysrhythmias
- Acceleration of Age-Related Osteoporosis

- Manifestation of previously asymptomatic cardiovascular disease
- Toxic Exposure



Medical Practice Problems

- Trauma & Acute Medical Problems
- Illness & Ambulatory Health Problems

- Renal Stone Formation
- Toxic Exposure

Behavior and Performance Problems

- Disorientation and Inability to Perform Landing, Egress, or Other Physical Tasks, Especially During/After G-Level Changes
- Poor Psychosocial Adaptation
- Sleep & Circadian Rhythm Problems

The Critical Path Roadmap represents an opportunity to implement an evolving program of research and technology designed from a “risk reduction” perspective to prevent or reduce the risks to humans exposed to the space environment (includes increased efficiencies). It has been vetted with the national biomedical community and will continue to be used as the guiding document for Bioastronautics research with increased emphasis on moving prospective countermeasures into higher readiness levels, for example in radiation research, clinical research, and medical technologies.

For OBPR to provide scientific evidence that can bear on the strategic research question of assured survival of humans traveling far from earth, there are critical questions requiring research products in five areas prioritized by the REMAP Taskforce: Clinical and Operational Medicine; Physiology (Integrated and Organ Systems); Radiation Health; Behavior and Performance; and Environmental Health. Some critical questions in each of these areas include:

What knowledge, tools and procedures are needed to enable best practices for providing medical care in space? The approach to ISS medical operations has shifted from a “stabilize-and-transport” line of defense, to the current a “stand-and-fight” mode of operations that provides for the capability to treat as many medical conditions as possible on orbit. Satisfying those criteria, including the capability to treat as many medical conditions as possible on orbit, requires provision of preventive measures, crew health and performance monitoring, clinical capabilities to treat and resolve medical contingencies, and a set of validated effective and efficient countermeasures. This requires enhancing onboard medical capabilities to enable the diagnosis, stabilization, and treatment of medical contingencies.

How does the human body adapt to space flight, to what extent do these adaptive responses compromise crew health, safety, and performance during and after space flight, and what are the most effective and efficient techniques to counteract those adaptive responses that place crewmembers at unacceptable levels of risk? Almost half a century of human space flight has identified profound changes in muscles and their strength, bones and their hardness, the ability of the heart and blood vessels to carry out their normal functions, the structure and function of brain circuits that control cardiovascular reflexes, posture, locomotion, perception of spatial orientation and, perhaps most importantly, changes in basic body functions such as immune function, susceptibility to infection, blood constituents, and nutrition. All of these changes contribute to human health, safety, and performance risks of space flight, and must be explored in a systematic scientific program to provide appropriate countermeasures to their negative effects that are specific to individual crewmembers, their roles and responsibilities, and mission length.

How can we protect human space explorers from the harmful health affects associated with exposure to space flight radiation environments? Radiation protection strategies for the crews living and working in space as well as their vehicle and equipment includes: acquiring the knowledge base that characterizes the radiation environment in space, on planetary surfaces, and in spacecraft; characterizing the crew health changes associated with exposure to the space radiation environments; reducing the uncertainties associated with measuring the radiation environments and establishing acceptable levels of risk. In addition, scheduling of space flight activities to avoid exposure to dangerous solar particle events, development of physical shielding using new materials to absorb or deflect dangerous radioactive particles. It important also to develop crew screening, diagnostic and repair strategies based on a better understanding of the mechanisms of damage at the level of genes, cells and tissues.

How can we provide an optimal environment to support behavioral health and human performance in space flight and afterwards? Space flight places small crews (between three to ten people) in a confined, isolated, dangerous and potentially lethal environment, where there is total dependence on individual skills and wits, as well as their ability to cohabitate and perform complex tasks as a group. The Mir Space Station was used to study psychosocial issues during long duration space flight. Psychosocial issues such as group tension, cohesion, leadership, and the displacement of negative emotions among space and ground support teams were studied. Important findings are being used to improve psychosocial support for selecting compatible crews, improved training for team building, training for individuals to identify potential problems, and new recreational supportive activities. OBPR research is beginning to answer behavioral health and performance questions about how to optimize countermeasure strategies to ensure psychosocial health, prevent circadian rhythm disruption, and neurobehavioral dysfunction.

“Assured Human Survival”: A Roadmap

Objective	2003-2007	2008-2012	2013-2017
Knowledge, tools, and procedures needed to enable medical care in space	• Establish clinical norms for human adaptation responses and determine acceptable levels of risk • Develop and implement a health monitoring and assessment system • Certify crews for 180+ day missions	• Ongoing assessment and verification of crew health and performance • Validation of countermeasure options • Test monitoring, diagnosis, and treatment regimens for medical care	• Demonstrate fully autonomous medical care capabilities to support medical contingencies for missions beyond LEO
Development of effective countermeasures to reduce human health risks related to space flight	• Characterize physiological changes as a result of space flight; establish acceptable levels of risk • Elucidate causative mechanisms of changes due to space flight • Develop and validate countermeasures in relevant environments	• Refine effectiveness and efficacy of countermeasure strategies on ISS • Test countermeasure strategies in the context of missions beyond LEO	• Validate the countermeasure strategy to enable a 1000-day exploration class mission involving gravitational transitions, high autonomy, and self-sufficiency
Protection from space radiation environments	• Measure and characterize the radiation environment on board the ISS, Mars transit, and on Mars • Determine and establish acceptable levels of radiation risks • Implement operational countermeasures	• Demonstrate in three 180-day periods on ISS that evidence based radiation countermeasures can keep crew within the limits of medically permissible exposure • Explore and implement new radiation countermeasures	• Assure, at a 95% confidence level, that the crew will not exceed the safe dose of radiation for a 1000-day exploration class mission
Optimal environment for behavioral health and human performance for space flight	• Determine the behavioral health and performance changes in ISS crews • Conduct research on the psychosocial interactions in isolated small groups • Research crew performance to determine countermeasure development	• Design, test, and evaluate countermeasures for behavioral challenges • Develop and evaluate crew selection and screening	• Demonstrate the prevention/treatment regimen in the context of optimized crew performance and compatibility in extended duration missions

Question 2: What must we know about how space changes life forms so that humankind will flourish?

Alternative question: How can humankind benefit from using space to probe the fundamental nature of life?

> **OBPR Research Areas:**
> - Cell & Molecular Biology (Combined with Molecular Structures & Interactions and Cell Science & Tissue Engineering)
> - Organismal/Comparative Biology
> - Developmental Biology

Quotes:

F. Turek: "..we have no idea how gravity interacts with life processes at the molecular, cellular, systems or behavioral levels. ISS provides a unique environment to began to probe the last frontier of how the physical environment has shaped life on earth."

R. Roberts and G. Whitesides: "We would argue that studying the effect of gravity on life requires the ISS, and that understanding these effects justifies the existence of the station. Understanding the relationship between gravity and life at all levels will require a partnership between biological and physical sciences: understanding how cells and organisms sense and respond to gravity will require us to understand a very broad range of phenomena."

Primary Outputs:

Identification of the response of select organisms to the space environment at all levels of biological complexity; information on the underlying mechanisms that guide the control and regulation of biological systems, characterization of genetic alterations that accompany exposure to changes in gravity; determination of the molecular and cellular damage caused by space radiation; determination of the way organisms sense gravitational loads and transduce the signal to determine self-motion, and directly and indirectly regulate vascular flow, bone and muscle size and structure.

Desired Outcomes:

Establishment of a "biological baseline" in space: an understanding of the effects of the space environment on fundamental metabolic and structural pathways and cells, systems and whole organisms, using model organisms of increasing complexity

Using space as a probe into the fundamental nature of life, identification of biological knowledge for use in human medicine and industry

Through the use of human cell lines and 3-d cell groups, identification of key intervention points in molecular and cellular pathways, leading to molecular-based human space countermeasures

Development and selection of key strains of organisms to be used in advanced life support systems.

Medical research on the ground will develop methods to target and mitigate the debilitating effects of problems associated with aging such as osteoporosis and muscle wasting.

Note:

This research area should be interdisciplinary, e.g. see Roberts and Whitesides quotation cited above. Also, from the ReMaP Task Force Report: *"Many of the observed physiological changes in living organisms under LEO are affected by fluid mechanics that, in turn, affects biological responses. Therefore, fundamental microgravity research in the physical sciences, which is closely coupled to analytical and numerical modeling, enhances the potential for understanding the results from experiments on biological systems."*

Description:

For life's entire history on Earth, one critical parameter has remained constant – the pull of gravity. For the first time humankind has the capacity to examine the role that gravity plays in life processes for long periods of time—weeks, months and years--in space. Just as studying life's interaction with environmental constants such as light and oxygen has shed fundamental insights into life's inner workings, gravity will also serve as a powerful probe into the fundamental mechanisms of living processes. To date, we have only limited understanding of how gravity interacts with life processes at the molecular, cellular, systems or behavioral levels. Space provides a unique environment to probe the last frontier of how the physical environment has shaped life on earth.

Exploratory biological research of the adaptation of terrestrial life forms such as cells and organisms (e.g., bacteria, insects, plants, animals) will result in new insights into the effects of gravity on biological processes. Because biological questions are amongst the most formidable as humans embark upon exploration beyond our planet, this knowledge will contribute to many aspects of NASA's strategic goal of exploration. In addition, the knowledge gained from this research will provide fundamental insights into general living processes with many applications on Earth.

To realize these contributions, OBPR must answer key questions at all levels of biological complexity. These range from understanding molecular and cellular changes, to understanding changes at the level of the whole organism, as well as the complex interaction of multiple species in closed environments. The critical questions include:

Does space affect life at its most fundamental levels, from the gene to the cell? The genetic code is the blueprint of life. Expression of this code and the subsequent formation of proteins and higher level structures in cells are fundamental processes that occur in all life forms on our planet. Does the novel environment of space alter fundamental biological processes at the molecular and cellular level?

How does long-term exposure to space affect organisms? What are the effects of chronic exposure to altered gravity and other space-related factors on normal physiology, metabolism, and performance of animals and plants? Are there limits beyond which organisms cannot adapt, and either suffer irreversible effects or perish?

How does space affect the development and lifecycles of organisms? Normal development and function of biological organisms and their various organ systems, the capacity of organisms to reproduce, and senescence processes form the cycle of life as we know it on Earth. Are these processes affected when they occur in space and what can we learn about the mechanisms of these processes by studying them in space? Of particular interest are those systems that sense, respond, and use gravity in the adult (e.g., balance system, bone, muscles, control of movement).

How do systems of organisms and their interactions change in space? Space is an extreme environment not just for individual organisms but also for groups of similar and dissimilar organisms. Parameters affected by the space environment such as gas exchange may have a major effect on groups of organisms. Is the organization of relatively simple communities such as microbial films and mats affected by the space environment? How will any such effects on the organism community and ecological scales affect our ability to assure astronaut health and provide for their life support in future exploration missions?

Knowledge from our research will provide critical strategic information for human exploration, ranging from selecting and adapting organisms for advanced life support systems to development of space countermeasures from studies on specific human cell cultures. The answers to these questions will provide a thorough understanding of the consequences of long-term exposure to space and, as importantly, provide novel information about the functioning of biological processes and systems on Earth.

Roadmap: What must we know about how space changes life forms so that humankind will flourish?

Objective	2003-2007 Building a biological baseline	2008-2012 Applications research: exploration and human health	2013-2017 Mission payoff
Molecules to Cells	• Genomics and proteomics in space for simple model organisms	• Elucidate key molecular mechanisms affected by space • Initiate development research for molecular-level counter-measures	• Underlying mechanisms of life's adaptation to space understood
Complex Organisms	• Genomic and proteomic studies in human & mammal cell cultures and tissues • Enabling plant research	• Fully controlled studies on higher organisms: impacts to space health • Test countermeasures in mammals	• Molecular basis of, and therapies for space health • Understanding of human response from animal models
Lifecycles: Development And Change	• Development studies in model organisms (c. Elegans, etc.) • Studies on genenetwor and drift over generations	• Organism optimization and selection research for space multiple generation studies on complex organisms	• Organisms adapted for life support
Systems of Organisms	• Microbial colony studies • Studies in simple model ecologies	• Directed ecological studies for life support • Pathogenicity studies: microbes to biofilms	• Establish robust ecologies to support humans on long-duration missions of exploration

Question 3: What new opportunities can our research bring to expand understanding of the laws of nature and enrich lives on Earth?

Quotes:

Sean O'Keefe: "as we look back and ask what was important about the ISS, it will be the scientific achievements that will be remembered."

ReMaP Task Force Report: "ISS research will form the basis of navigation and measurement technologies (clocks and GPS) vital for life and travel in space, and improved life on Earth.

NASA Space Act of 1958 (As Amended): The Congress directs NASA to "seek and encourage to the maximum extent possible the fullest commercial use of space."

ReMaP Task Force Report: "the 1998 Commercial Space Act established as public policy the commercial use of ISS and NASA's role as a facilitator to utilize ISS for commercial purposes."

Primary Outputs:

Original and innovative scientific results from select examinations of fundamental laws of matter, including equivalence principle and relativity; understanding of the microgravity effect on gene expression, membrane architecture, cytoskeleton and subcellular organelles; new insight into self-assembling, colloidal fluid systems, microstructure of materials, and combustion kinetics with application to, among others, health care, photonics, engines, nano-electronic devices and micro-robotics; world's most accurate clock(s).

Strengthened engagement of our research and educational institutions in the exploration and development of space, improving the skills of our scientists and engineers in areas of technological and national importance.

Partnerships between NASA and the private sector, or between NASA sponsored commercial space centers and the private sector, that enable companies to further their research in new or improved products using insights gained from laboratories on Earth or facilities in space on board the International Space Station.

Products emerging into the marketplace that are the direct result of collaboration with OBPR's commercial space research program including the commercial space centers.

Increased leveraging of corporate resources (in-kind and cash) that demonstrates commercial sector interest in and investment in space-based research.

Desired Outcomes[2]:

Scientific achievements that will lead the integration of the human space program and especially the International Space Station into the research and development assets of the U.S. and the world, expanding participation in the space program to important communities of engineering and scientific research.

Recognition by the technical, professional, and corporate sector and the general public that space research materially contributes to health and well-being including economic well being on Earth.

A robust commercial sector in biotechnology, agribusiness, communication and advanced materials that is the direct result of collaboration with OBPR's commercial space research program.

New research ventures that advance future commercial research objectives including commercial sector involvement in space exploration initiatives.

Description:

> *Albert Einstein: "The important thing is not to stop questioning. Curiosity has its own reason for existing. One cannot help but be in awe when he contemplates the mysteries of eternity, of life, of the marvelous structure of reality. It is enough if one tries merely to comprehend a little of this mystery every day. Never lose a holy curiosity."*

Fundamental research, from which valuable knowledge is obtained, has been the centerpiece of our contribution to NASA's space-based research for the 20 years of research on the Shuttle, based on our belief that scientific research is the engine driving the expansion of the world's economy. Economic analyses demonstrate that over half of the economic expansion since the Second World War was driven by the development of new technology. Further, nearly 75% of the citations in U.S. industrial patents refer to papers derived from government-sponsored research.

History has shown that creative scientists and engineers working on novel questions are prone to generate new solutions to resolve them, and these new solutions frequently find applications beyond the science research realm. These applications are often unpredicted by the original research team. Our previous experience also taught us that the behavior of biological and physical systems in the absence of gravity is surprising, intriguing, and insightful. Theoretical predictions frequently need re-examination and refinement because microgravity-based experimental results often differ from expectation. There is proven value in such findings, even as they surprise and confound us: as the great

[2] Regarding "Desired Outcomes", "breakthrough findings" are desired, but these are impossible to predict, as noted from 'GPRA for Research', NRC 2001: "when knowledge is the objective, its form is unknown, and its discovery is often serendipitous. That kind of objective defies the use of conventional metrics."

physicist Neils Bohr once said, *"We will not have any understanding until we have some contradictions."*

With the arrival of the International Space Station, the scientific community has an unprecedented opportunity to expand its tools of scientific exploration in fields of great importance. The ISS is providing opportunities for the physical and engineering sciences to address the breadth of questions of this era with new tools. This opportunity is attracting a large and growing research community from academia and industry, and early results from experiments aboard the ISS are already making noteworthy contributions to answer our four most basic questions:

How does the space environment change the behavior of <u>physical and chemical processes</u> and the technologies that rely on them? When people leave the Earth, they leave behind one of the great constants of life and technology—the force of Earth's gravity. Many physical and chemical systems –the systems that create the materials, provide the energy, and maintain the environment of a technologically based society- are profoundly influenced by gravity. The effect of gravity on these systems is a challenge to engineers and mission planners, who must rely to a great extent on theory and models to predict the performance of mission-critical systems. At the same time, it is an unprecedented opportunity to scientists, who see the possibility of controlling the effects of gravity as the opening of a new window into the principles of physical and chemical processes associated with fluids, combustion and materials. This possibility offers the promise of better understanding of nature and of the advancement of technology. Space research on physical and chemical processes will give aerospace designers the tools they need to make future missions possible. This same effort will make significant contributions to the new materials, power generation, and manufacturing technologies of the twenty-first century.

What can we learn about the organizing principles from which <u>structure and complexity</u> arise in nature? Complex systems study the dynamics of interacting elements, and the patterns and structures that result from those dynamics. This field connects seeks to explain and predict how order arises from seemingly chaotic interactions. Examples of such systems include grain coarsening in metals, the evolution of structures in solidifying alloys, order-disorder transitions in systems of fine (colloidal) particles, granular flow in sand dune migration, flowing foams, soil failure under stress. Theories of complex system dynamics are applied in areas as remote as atmospheric turbulence and traffic modeling. The advent of large-scale computing has provided the computational basis for recent progress in theory, but fundamental experimental data is limited. Space research provides opportunities for scientists to conduct benchmark experiments with unparalleled clarity. Planned and current projects examine coarsening of solid-liquid mixtures of metals, pattern formation in alloy solidification, the mechanics of soil failure under stress, flow of sand grains, and the mechanics of flowing foams. Future NASA research on board the ISS will include projects involving a new material, colloidal crystals, formed by a self-assembly process from micron-sized particles. Colloidal crystals are the subject of intense interest in the applied physics community because of their potential as the basis for optical signal processing device technologies.

Where can our research advance our knowledge of the <u>fundamental laws</u> governing time and matter? The central objective of research in this area is to understand the laws that govern the behavior of the physical universe. These laws are represented by models that describe the forces present in the universe and their effects on matter. Achieving greater clarity and accuracy in these models raises our understanding of the universe itself, and eventually gives us the tools to create new capabilities. Several of the physics experiments aboard the ISS, because the space environment enables them to achieve unprecedented precision in their measurement of physical constants, will allow exploration of concepts like the breakdown of Einstein's theory of gravitation, the properties of the electron, and other outstanding questions. The recently developed capability ability to use lasers to levitate and position atoms and molecules at extremely low temperature is opening up a new field of atomic physics. As this area matures, it will provide new possibilities for the manipulation and application of quantum characteristics in areas like quantum computing, quantum data storage, and highly precise clocks. Space provides a valuable tool to investigators in this field, because the near-absence of gravity allows levitated atoms to be confined longer and with less pressure than is required on Earth. This capability has attracted a distinguished research community, including several Nobel laureates, to develop research projects for ISS facilities. Space research also enables scientists to examine the characteristics of quantum fluids, primarily liquid helium and its isotopes. These helium systems provide the best models available to physicists interested in advancing our understanding of superfluidity, cooperative phase transitions such those describing superconductivity, and other priorities of contemporary physics.

What are the fundamental physical, chemical, and <u>biophysical mechanisms</u> that drive the cellular and physiological behavior observed in the space environment? NASA has pioneered interdisciplinary research between the physical and biological sciences for over 20 years. NASA has made significant contributions through its work in areas like the tissue engineering, where NASA-sponsored research studies the effects of mechanical stresses on cell physiology, and in newer work in areas like biomolecular physics, where processes such as biological self-assembly are examined. NASA-sponsored research on the role of gravity in biophysical separations technology led to design revolutions that are now incorporated in state-of-the-art preparative and analytic molecular separation devices. NASA-sponsored work in biological macromolecule crystallization has helped put this essential component of structural biology studies on a systematic, scientific foundation. NASA research in tissue engineering has produced a new tool, the NASA bioreactor, which controls mechanical stress on mammalian tissues during culture, similar to the control sought through space experiments, and is being used by hundreds of scientists in biomedical research today. NASA's future plans include a new generation of space experiments investigating the nature and effects of gravitationally-derived stresses on cells and tissues in culture, in the Biotechnology Facility aboard the ISS, and an effort in integrated science that will pursue new insights to problems of health in space through close collaboration between experts in medicine, biology, engineering, and physical science.

While these questions are utilized as a general organizing tool for our research, OBPR remains committed to providing tangible benefits to people on earth. As noted by the Committee on Microgravity Research of the Space Studies Board in its 2002 report, Assessment of Directions in Microgravity and Physical Sciences Research at NASA, *"NASA-supported investigations in fluids, combustion, materials science, and fundamental physics have had a major impact on these fields—thus PSD [OBPR's Physical Science Division] has been successful in funding high-impact research. Moreover, as NASA has successfully attracted a cadre of distinguished investigators as well as promising young investigators in these areas, there is a very good probability that high-quality research will emerge from these communities in the future."* We intend to continue this kind of work as an integral part of our mission of scientific exploration. The user community will be able to recognize our support of our more traditional discipline expertise – biomedicine, biotechnology, combustion science, fluid physics, fundamental biology, fundamental physics, materials' science – and the application of this expertise for terrestrial benefits and national priorities.

SIDEBAR: As an example of how the ISS can contribute to the fundamental research in these important areas, Nobel Laureate Bill Phillips wrote the following about some of OBPR's experiments in space that address the frontiers in physics:

Gravity

Gravity was the first force of Nature to have a modern description. In 1687 Newton explained falling apples and the orbit of the moon in a single, a quantitative theory with predictive power. He also explored the mystery of 'Equivalence', the strange observation, first noted by Galileo, that objects of different mass fall at the same rate.

Twentieth century view

Assuming Equivalence, Einstein modified Newton's theory. His General Theory of Relativity is our current theory of gravity and reveals such wonders as black holes. It is one of the great scientific revolutions of our time. Another is quantum mechanics, the strange but accurate description of the submicroscopic world of atoms and subatomic particles. These two theories not only revolutionized our scientific and philosophical views of the universe, but also our everyday lives (just as Newton's mechanics enabled the industrial revolution). Without quantum theory we would not have modern electronics and without understanding General Relativity, we could not operate the global positioning system (GPS provides precision navigation for commercial aircraft and for military operations).

Where is the frontier today?

Although these two theories are the most successful of all time, Einstein's theory does not fit with quantum theory. Quantum theory unified all forces besides gravity into a single framework called the Standard Model, the culmination of 40 years of theory and of experiments with giant colliders ("atom smashers") like those at Brookhaven, SLAC, Fermilab and CERN. Today, 21st century experiments in space can help us determine where General Relativity fits into the rest of physics.

What are the other forces of nature and how is gravity different?

There are two other classes of forces of nature, the sub-atomic forces (which bind the atomic nucleus and are responsible for radioactive decay), and electromagnetism. Remarkable, those forces are each described by quantum theories of the same mathematical form. Einstein's theory cannot be so described. Despite tremendous effort by physicists the world over, unification of the two great achievements of the 20th century physics, Quantum Mechanics and General Relativity, remains a grand challenge that demands experimental attention.

What would we gain with a unified theory?

The most profound advances in physics occur when differing descriptions are unified. Maxwell, in 1865, united electricity and magnetism into a single theory of electromagnetism. Maxwell's unification provided a new explanation of light and predicted radio waves, ushering in the modern technological age. In the early 1900s Schrodinger, Heisenberg, Einstein, Bohr and others shook the foundations of modern physics by introducing the quantum theory providing a unified view of particles and waves. Without the quantum theory, we would no have invented transistors or lasers, the workhorses of modern technology. Gravity has yet to join a unified theory of nature. But, with such a unified theory, we might hope to understand some of the deepest remaining mysteries of the universe like the Big Bang.

Can research in space help unify the theory of gravity and the Standard Model?

Recent years have seen a flurry of activity with the goal of developing just such a unified theory. Super-symmetry, string and brane theories are all efforts to go beyond Einstein to produce a unified picture, and they imply violations of General Relativity. So far, no such violations have been seen, but thanks to tremendous strides in the techniques of experimental physics, and the unprecedented opportunity to make measurements in the laboratory of space, instruments such as super accurate clocks are now being built for space-borne experiments that can probe Einstein's theory at an unrivaled level. By committing Fundamental Physics to the Adventure of Space, we may approach the final frontier where we solve some of the most enduring mysteries of the universe and reveal the technologies of the future.

How can research partnerships – both market-driven and interagency -- support national goals, such as contributing to economic growth and sustaining human capital in the areas of science and technology?

> *Jim Corbonari, CEO, PentaPure: "We've been involved in space-based research with BioServe for over a decade and the investment has been well worth it".*
>
> *Ray Lam, Natural Products Research, Bristol-Myers Squibb: "Our collaboration with NASA not only puts our researchers in the forefront of science, but also gives us the opportunity of being first in our field to develop new technologies and products".*

This portion of our research program has two elements: agreements with other Federal agencies and agreements with the private sector. In the first element, OBPR has over 65 project agreements with about 40 agencies. Partnerships involve the National Cancer Institute, the Institute on Aging, the National Eye Institute, the Air Force Research Laboratory, the Department of Energy, and many others in pursuit of mutually beneficial sponsored research, or provision and exchange of technical expertise. The agreements can be in support of any of our Organizing Questions.

Similarly, OBPR is committed to helping American industry demonstrate the competitive advantage of the space environment, enabling companies to create new products and services while supporting the development of answers to our Organizing Questions.

Research partnerships also support two important national goals. National space policy supports the government role to stimulate business investment in the development of new markets and industries to maintain and enhance U.S. economic competitiveness. Success in such space development means new businesses, higher quality jobs, greater economic growth, and new products and services. At the same time, research partnerships necessarily support space exploration, providing new knowledge and technologies to support space systems and humans as we live and work in low-Earth orbit and beyond. Industry may bring the efficiency of the marketplace and the profit motive to support exploration goals. We envision that as long-term space exploration expands, and as requirements increase, industry will play a greater role in providing new infrastructure and capabilities for human presence beyond low earth orbit.

In addition, research partnerships facilitate the use of space (and appropriate ground-based activities) for development of commercial products, services and infrastructure. This element of the OBPR program couples NASA and private sector technology to the advantage of both and participates in the incubation of private sector enterprises that use space on a profit-making basis. A guiding factor is that industry puts its own substantial capital at risk. Industry provides the bulk of the resources to pursue a research direction to meet business goals and the needs of the marketplace. Industry also provides *all* the resources required to bring products and services that result from space research to market.

Basic questions underlie investments in space, especially when industry and government are partners. Industry and government address these questions as they determine whether to pursue a path together as partners. Industry must make business decisions and government must decide the appropriate role for public support, and risk mitigation, for the space sector:

- Does the space environment offer competitive advantage that justifies using space to pursue research, or is ground-based research the better approach?
- Is the initiative economically feasible to seize competitive advantage—can a business case be made for the use of space?
- Is the industry partner prepared and qualified to take the resultant product to market?
- Is there a benefit to the public through the creation of a new or improved product or process that enhances the quality of life?
- Does the research support national goals, such as contributing to economic growth of the nation through increased GNP and sustaining human capital in the areas of science and technology?

This element of the research program is implemented today through the Commercial Space Centers (CSCs), which are non-profit partnerships of commercial, academic and governmental entities that conduct space research and development projects. CSCs are established by cooperative agreements with NASA, in which NASA provides base funding at approximately one million dollars per year per CSC plus funding for multi-user instruments. Industry provides cash and in-kind investments plus funding for proprietary experiments and technology test-beds. For each dollar of government support, industry today provides approximately $1.5 of equivalent support. Each CSC focuses on a specific research discipline. Currently, over 160 industry partners are actively pursuing over 80 commercial product lines. Examples of the areas of research are shown below:

- Biotechnology: including plant-based pharmaceuticals, increased antibiotic production rate, protein crystal grown, biomaterials, microencapsulation of drugs
- Agribusiness: improved crop development, enhanced wood products through research in lignin formation, food safety
- Materials Processing: zeolite crystal growth, improvements in casting processes, improved fire suppression technology, improved fiberglass
- Engineering Research and Technology Development: satellite and hybrid communication networks, satellite components, space power (generation, storage, management)

Expand Understanding of the Laws of Nature and Enrich Lives on Earth: The Roadmap

Objective	2003-2008	2009-2015	2015 Forward
Physical and Chemical Processes			
Advance Earth-based heating, cooling, power generation, and fluid control technologies through new discoveries in fluid and thermal sciences	• Complete first generation physics-based models of nucleate boiling with space data. Develop flow boiling experiments for priority surfaces. Develop predictive models for flow and wetting in vessels, microchannels and soil pores	• Provide predictive models for flow boiling over 0-1g range. Validate with flight tests. Demonstrate technologies for high-efficiency heat transfer on Earth. Extend wetting results to microfluidic controls and fuel cell designs	• Test high-efficiency heat transfer principles in flight experiments. Develop chemistry-based wetting controls to improve performance of heat transfer surfaces
Contribute to national efforts to increase fuel efficiency and reduce pollution in combustion systems through the unique insights space experiments offer into reaction processes and mechanisms	• Complete analysis and implementation of soot formation model, validate with experiments. Extend results to more complex fuels. Develop dataset for spray combustor modeling.	• Probe effects of turbulence in gaseous flames through flight experiments. Combine high-pressure and spray effects to provide results relevant ot practical combustion systems	• Transfer turbulence and spray results to industry to achieve combustor design improvements, cleaner and more efficient diesel engines
Develop interdisciplinary integrated science solutions, combining the skills of the engineering and physical sciences, to address the challenges of twenty-first century discovery	• Establish research program fusing capabilities of computational materials science, condensed matter physics, chemistry, and transport phenomena engineering, to examine the feasibility of flight research	• Demonstrate nanotechnology-based self-healing materials, power generation and energy conversion concepts on Earth Explore physics of these devices through flight research.	• Integrate research results with engineering through institute-based efforts. Examine nanotechnology-based concepts for multi-functional adaptive materials.
Structure and Complexity			
Gain insights into self-assembly, pattern formation, and phase transition, as fundamental paradigms for the processes leading to order and structure in nature	• Conduct a series of flight experiments on phase transitions, self-assembly, and solidification dynamics • Advance theoretical foundations describing the origins of structure in complex and turbulent systems	• Incorporate initial flight results into new processing technologies for advanced aerospace materials • Conduct flight experiments examining the dynamics of turbulence and structure in complex and reacting systems	• Integrate program results into evolving strategy of advancement in structural and sensor materials meeting aerospace requirements. Apply knowledge of complex and reacting systems to design of exploration systems
Produce novel materials of scientific importance, using the control of gravity to achieve unique process conditions	• Develop and demonstrate new experimental technologies for materials synthesis in space, to explore the characteristics of carbon nanotubes, metallic glasses, colloidal crystals, and other advanced materials	• Establish series of flight experiments to probe scientific questions underlying nanotube formation, properties of metallic glasses, self-assembly of colloidal photonic devices	• Transfer fundamental scientific advances in novel materials synthesis to commercial technology development

Fundamental Laws			
Explore the quantum world and seek applications for newly discovered properties of matter	• Develop flight facility and experiments for a coordinated series of investigations on the superfluid transition of helium • Develop technologies for a new class of space-based research in atomic physics	• Create new forms of matter through ultracold atom technology, as Bose-Einstein condensates. Test theories of atom lasers	• Develop and test concepts for matter transport using atom lasers. Explore properties of Bose-Einstein condensates for potential use.
Test our understanding of the nature of gravity and its relationship to space, time, and the other forces of nature	• Develop and fly new ultraprecise clock technologies for relativity experiments aboard the ISS • Develop free flyer concepts for gravitational physics research	• Fly state-of-the-art tests of inverse square law and other fundamental postulates of physics. • Launch first free-flyer missions examining basis for unified field theory of space-time	• Establish evidence for existence of quantum gravity. Probe gravitational evidence of remnant non-conserved fields from early universe
Biophysical Mechanisms			
Provide tools for understanding, diagnosing, and treating health problems by coupling advances in biosciences research with the analytical and systems capabilities of the physical and engineering sciences	• Establish and validate models for the cellular mechanisms responsible for adaptation to fluid stresses. • Develop technologies for in vivo quantification of key physiological signatures	• Develop and test control strategies for cellular response and transport changes under fluid stress • Expand dissemination of NASA technologies to biomedical research through institute-based interactions	• Develop new tools for biomedical diagnostics based on technologies established for low temperature physics experiments
Establish and validate space-based tissue engineering as a resource for biomedical research	• Develop and operate first generation tissue engineering research facilities in space, allowing national community to validate results. Refine technologies for Earth-based bioreactors, verify stress-reduction analogy to space flight	• Extend space station research to complex and functionally differentiated tissues, such as tumor models.	• Establish scientific basis to duplicate the capabilities of flight-based tissue engineering in Earth-based bioreactors
Provide the structural biology community with space-derived tools to solve challenging and important protein structures	• Establish and complete validation space experiments demonstrating value of space-based crystal growth to structural biology. Develop new technology for high productivity crystallization on ground and in space	• Automate flight-based crystal growth to serve national community. Develop definitive screening criteria for flight candidate proteins	• Assess needs of structural biology community and respond where required with new generation of flight technology

Question 4: What technology must we create to enable the next explorers to go beyond where we have been?

OBPR Research Areas:
- Environmental Monitoring & Control
- Advanced Life Support
- Enabling Knowledge and Technologies for Propulsion & Power
- Human Factors Engineering
- Fire Safety
- Fluid Stability and Dynamics
- Phase Transformation
- Commercial Engineering Research and Development

Quotes:

ReMaP Task Force Report: "The central and paramount challenge for human exploration of space is to provide an environment consistent with the sustained existence of personnel outside of Earth's atmosphere…. many of the challenges in this area are potentially limiting for the next generation of human exploration missions."

ReMaP Task Force Report: "The research directly addresses challenges at the interface between the physical sciences, engineering, and integrated systems for human exploration in space. This research supports the long-duration (~ 20 years into the future) vision of NASA for space exploration."

L. Zoloth: "the crews are public servants, voluntarily undertaking a task that is difficult, highly risky and technically demanding. In this way the crew need workplace protections, similar in nature to how we protect soldiers, police and firefighters."

ReMaP Task Force Report: "Without advanced propulsion systems and power sources, human exploration beyond LEO (Mars) will be impossible."

Primary Outputs:

Design specifications for advanced sensors, components, and subsystems with proven performance in space environments; and regenerable closed life support systems and their validation and analyses. Future life support and environmental monitoring operational systems that have targeted improvements in terms of lower mass, power and volume while allowing for increased reliability. Microgravity–validated databases for materials flammability, early fire detection, extinguishment strategies and instrumentation. Innovative materials implementation supporting the deployment of new propulsion systems, microgravity-tested experimental breadboards for thermal and power management or conversion for spacecrafts and extra-terrestrial sites. Microgravity-based technology for in-space fabrication of components of large structural or functional engineering sub-systems.

Desired Outcome:

Development of new technology options, for selection by mission designers and planners, for reduced gravity environments ranging from specific components to entire subsystems that lessen the required mass to orbit, provide technical capabilities to travel beyond LEO, maximize resource utilization, and enable self-sufficiency far away from Earth.

Description:

> *Dr. F. R. Moulton, University of Chicago astronomer, 1932: "There is no hope for the fanciful idea of reaching the moon because of insurmountable barriers to escaping the earth's gravity"*
>
> *Thomas Paine: "We have it in our power to begin the world again."*
>
> *Arthur C. Clarke: "A sufficiently high level of technology is indistinguishable from magic."*

NASA's vision for its activities in the early 21st century includes establishing the feasibility of and laying the groundwork for a new era in history, the era in which human beings inhabit environments beyond the Earth. Looking beyond the space station program, succeeding generations of human missions into space will embody progressively greater levels of self-sufficiency and more complex technological requirements. The extension of human life beyond low earth orbit will require that the explorers be equipped with a spectrum of technologies to support life and make use of the available resources on the way to and at their destination.

What research and technology development is required to reduce the required up-mass, volume, and power of the next generation of autonomous, highly reliable spacecraft sub-systems? *Objectives/Endpoint: Reduce the required life support mass to orbit and beyond by a factor of 3 by 2010 through enabling knowledge and technology. Prevent or reduce crew health, safety, and performance risks associated with crew habitation in the spacecraft, during IVA or EVA. Improve fluid-dependent vehicle systems for operation in variable gravity, improve performance and reliability of advanced life support systems using two-phase technology.*

Exploring beyond low earth orbit (LEO) and making use of what is discovered in new environments requires the basic tools already developed on Earth for energy production and recycling of essential life support components (e.g., air and water). Unfortunately, these technologies have been developed and optimized on Earth and many, especially those involving fluid processes, will perform quite differently in reduced gravity environments. Over the next ten to fifteen years, OBPR will build the enabling knowledge and technology base for exporting the technology processes developed on Earth to new, reduced gravity environments. Also, current spacecraft and life support technologies rely on continual re-supply from Earth, therefore, it is logistically difficult and prohibitively expensive to venture much beyond the current limits of LEO due to the sheer mass of the systems required. For example, the estimated mass required on orbit for the Environmental Control and Life Support System (ECLSS) during the lifetime of the ISS is over 122,000 kg (or 270,000 lbs).

Dramatic reductions in the amount of consumables required and ultimately in the overall mass of human support technologies are required for further exploration of the solar system. To address these needs, OBPR's Advanced Human Support Technology (AHST) Program has set a goal of reducing the mass of a life support system by a factor of 3 over the next decade. To achieve this reduction, current physical and chemical systems need to be greatly improved and integrated with bio-regenerative systems that rely on microbes and higher plants to process crew waste, recover nutrients, recycle air and water and provide fresh food. These improvements include a potential annual savings of over 900 kg (or 2000 lbs) of upmass with the incorporation of a Sabatier reactor in the ISS environmental control and life support system (ECLSS).

Fluids and transport processes occur in a number of systems and subsystems that, at least based on terrestrial performance, may be applicable to a variety of mission enabling technologies such as water reclamation systems, thermal control, air quality and CO_2 removal. However, in most cases, the effect of weightlessness on the behavior of fluids in these systems has been assessed only qualitatively, even if at all. Because extrapolation from ground-based systems is not possible, there is a clear need for research. For example, many of the systems or processes under investigation involve fluids, typically liquids, and, even when air is involved, condensation is often a factor. The relative distribution of the liquid and air volume is no longer dictated by gravity, but rather by surface tension (or capillary) forces and by the chemical properties of the water-air-solid interface. OBPR's research program will develop innovative concepts and demonstrate technologies in such cross-cutting areas as new flow and thermal control and management schemes using multi-phase systems for thermal control and energy transfer. A key objective of this strategic research is the attainment of a comprehensive body of knowledge and flight-worthy technology that will serve as a lasting foundation for space development. As such, workshops were held recently with experts inside and outside NASA to capture the state-of-the-art understanding, mission requirements and research needs in exploration-related areas such as Thermal Control Systems, Fluid Management, and Environmental Sensors. This information serves as the foundation for our direction in technology development.

What research is required to develop safe, efficient and economical in-space transportation for travel beyond LEO? *Objectives/Endpoint: Develop the low-gravity knowledge base in materials science, fluid and transport processes, and high temperature chemical reactions to support technological advances in nuclear-electric and other propulsion systems. Introduce a set of knowledge-based design tools for the development of materials with pre-defined properties and performance by 2012.*

NASA's missions require propulsion systems that can extend to the outer reaches of the solar system and beyond. While present-day technology can provide propulsion systems that can achieve those goals, they are relatively low in efficiency, resulting in trip times that are much too long and in limited payload size and complexity. In particular, significant accomplishments in materials technology are required to achieve the efficiencies that will make future propulsion systems viable. For example, OBPR will carry out fundamental materials' science research to support technological advances in electrode materials for electric propulsion engines, in fuel material, reactor cladding, and heat radiator low-mass materials for nuclear propulsion, and in advanced low-mass materials for solar sails and inflatable structures for aero-capture technologies.

Important elements of spacecraft sub-systems involve heat transfer and rejection. Typical sources of unwanted heat include waste energy from power generation, from the operation of electronic components, from biological processes or from solar radiation. Because of their advantages, such as long life, and low mass and power requirements, two-phase systems have been the foci of attention for a long time. OBPR will investigate a range of approaches such as Multi-phase Heat Pipes, Capillary and Mechanical Pump Loop Heat Pipes, and Electro-Hydrodynamic Devices in order to improve the heat rejection capacity and reliability, and to lessen mass and volume requirements.

Examples of research areas are: two-phase flow systems for low-gravity operations in proposed space power systems such as the Rankine cycle, development of space-based experiments in nucleate pool and flow boiling to resolve microgravity technical issues such as dewetting and quenching, two-phase accumulators instability, and the operation of manifolds, development predictive model for liquid-vapor interface dynamics, location, and stability for fuel (cryogenics) tank configurations in low gravity, and implement passive and active interface control techniques, and the use of ground and space-based research to identify and to eliminate gaps in knowledge preventing the design of materials achieving theoretically predicted performance

What research and technology innovation is required to provide affordable, abundant power for operations, including the utilization of *in-situ* planetary resources? *Objectives/Endpoint: Conduct the required research and introduce the needed technological innovations to provide the necessary resources for exploration beyond low Earth orbit and at destination on extra-terrestrial bodies. Introduce prototype systems for low-gravity waste reclamation and energy conversion by 2012. Enable the future of human exploration by providing the scientific knowledge and technologies for engineering implementation by 2015.*

In-space resource processing and production is critical to reducing the weight of spacecraft and payloads, the primary cost driver in exploration missions and requires the understanding of the properties of the indigenous resources and gravity dependence on processes and resulting properties. The emphasis here changes from producing new science knowledge to experiments that enable, validate or optimize, processes and in-space manufacturing technologies essential to the robotic and human exploration of space. In-situ energy production, transfer, and storage are crucial technologies; since the availability of energy is rate limiting for many processes in-situ, energy production research will be required.

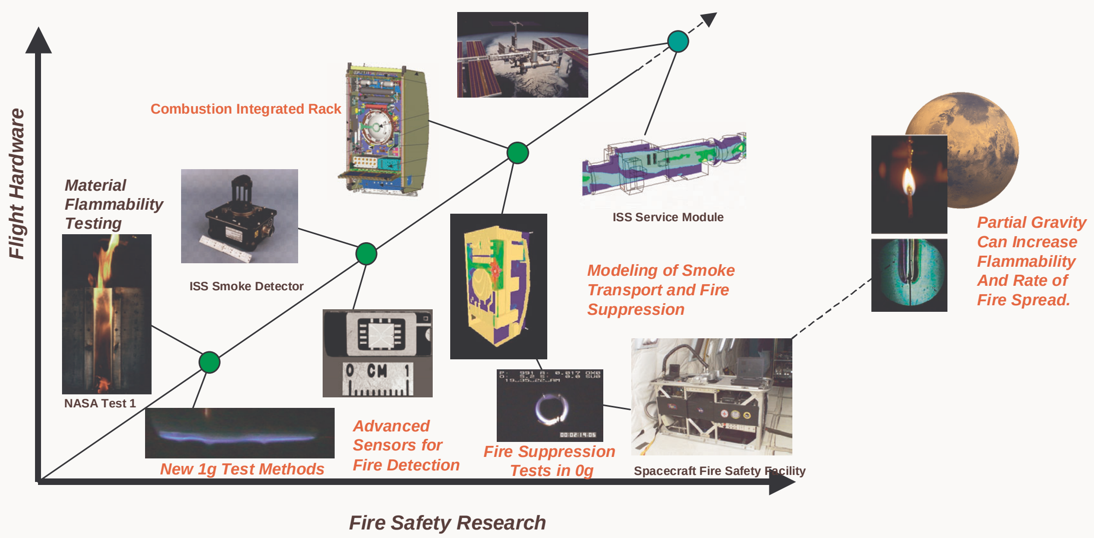
Almost all aspects of in-situ resource utilization (ISRU) processes involve chemical conversion of matter from one form to another usable form with the supply of energy. Many of the processes that have been identified thus far to process Lunar and Martian soil or atmosphere involve high temperature reacting flows, which involve flow through porous media, catalytic surface combustion, and multi-phase flows which are strongly influenced by the gravitational environment. Examples of specific research areas are: The development of various chemical reactors for conversion of in-situ resources to useful materials, low and microgravity waste incineration development of low-g compliant system for reclamation of bio-waste and conversion into electricity, the development of various types of process heaters to be used in microgravity or reduced gravity environments, and the development of microcombustors for various applications, notable extravehicular activities. Fabrication of components during space missions will be one of the key elements for developing a self-sufficient space exploration capability. Specifically, in-space fabrication could reduce reliance on spare parts supplied from earth and will enable production of components and deployable structures that cannot be launched from earth either because they are cost or size prohibitive or because they cannot withstand launch loads. Fabrication conducted within the environment of a spacecraft needs to consider parameters such as variable gravity levels, different pressure and temperature conditions. Research is needed in these critical areas of advanced materials and in-space fabrication processes: habitat and deployable structures, thermal protection systems, electronic and photonic materials, and dual or multi purpose materials. The need for research includes the study of fabrication and assembly of parts and devices outside the confines of a space vehicle to add large elements to an existing outpost, the fabrication of mission-specific devices to enhance safety or effectiveness. These "*free space*" operations present a unique set of technical challenges created by the space environment. High vacuum, intense radiation of many types, large temperature gradients, high momentum objects and levels of gravity ranging from microgravity to localized artificial gravity characterize this environment. The need for a capability to process materials and construct objects of large dimension under such extreme conditions demands a thorough study of the behavior and properties of materials that will enable imaginative solutions to develop robust technologies.

What research and technology development is needed in automated sensing, and autonomous controls architecture to ensure that the crew is living in a safe and healthy environment? *Objectives/Endpoints: Develop advanced technologies for environmental monitoring and control systems that reduce mass and logistics and increase crew health, safety, and performance.*

Real-time and highly autonomous environmental monitoring and control systems will be required to ensure a healthy and safe environment for the crew and allow them to respond rapidly and effectively to an off-nominal condition or event. To meet these needs, advanced sensors are being developed to detect, identify and quantify contaminants in the air, in water, and on surfaces For example, real-time, long life, high fidelity miniaturized sensors to monitor gaseous and aqueous chemical contaminants, and to improve microbial monitoring of the spacecraft environment, as well as advanced control systems for integration across sensor platforms.

Fire is one of the most feared hazards in spacecraft. There have been at least six pre-fire incidents on-orbit in the Shuttle history, and two serious fires in the history of the Russian space station program. There is reason to believe that the application of microgravity (or perhaps normal-gravity) fire-safety practices to extraterrestrial environment will not provide adequate safety margins. For example, fire behavior in 1/6 or 3/8's earth gravity cannot be quantified by interpolation between findings in microgravity and normal gravity. Fire safety on extraterrestrial habitats will require considerable research, technology, and design information on material and configuration controls, detection systems and alarm criteria, and fire-suppression systems specifically dedicated to the peculiarities of fire behavior in this planetary environment. OBPR will carry out the necessary research to establish design criteria for material flammability and combustion products, for fire detection approaches and reliability, and for fire suppression strategies.

Benefits to date from fire safety research are listed below. Some planned areas for future research are shown in red.



Previous applications of research findings to NASA's spacecraft fire practices and policies:

- Shut off ventilation flow upon start of fire event, rather than deploy a fire extinguisher.
- Recognition that margin of safety presupposed for material flammability in microgravity is in fact absent.
- Recognition that smoke particles in microgravity are different, changing the needed sensitivity in smoke detectors onboard spacecraft (and then tested the ISS and STS smoke detectors against 0g smoke).
- Redesign of protection from fires similar to that which occurred on Mir

In the area of radiation protection, we will be developing transport codes that predict the behavior of various elements when exposed to typical space radiation spectra such as galactic cosmic rays (GCR), solar flares and other high-energy radiation. We will identify suitable candidate materials to sufficiently protect the crew living quarters from hostile radiation environments, with the possibility of using special shelters during intense periods of solar activity. It is anticipated that these materials will be of most use if they also qualify as engineering materials with good structural properties. The final outcome of this work is anticipated to be a database of the behavior of engineering materials in a cosmic environment, with a representative sampling verified by experimental results.

What research and technology development must be achieved to enable optimum crew performance and productivity during extended isolation from Earth? *Objective/Endpoint: Increase crew productivity and performance by decreasing the amount of available crew time through improvements in procedures and stowage design, communications effectiveness, systematic labeling, and revised computer interfaces.*

To safely undertake long duration missions beyond low earth orbit, we also will need to understand how humans living in extended isolation will interact with their highly complex spacecraft environment, and with each other. Research in space human factors engineering will address the human performance-related risks associated with living and working for prolonged periods in the highly isolated and confined conditions of long duration space flight. Systems with capabilities for effective communications between space and ground crews, expert systems for crew training, skill retention, and to aid decision-making and modeling for complex missions, tasks, and workloads. Development of minimally invasive technologies to monitor individual and group performance and the effects of the spacecraft environment such as noise, vibration, and other human factors variables on that performance. Design specifications for upgraded human factors engineering requirements including design features to maintain performance and increase productivity, adding many hours per week of extra crew time through greater efficiencies and reduced system maintenance. In addition, spacesuits serve as a significant part of the ‘crew environment’ during extravehicular activity. The spacesuits developed for the Space Shuttle and International Space Station programs will not be adequate for extended duration missions beyond low earth orbit. Research must be undertaken to support advanced extravehicular activity that will enable humans to explore other worlds.

Important elements of spacecraft sub-systems involve heat transfer and rejection. Typical sources of unwanted heat include waste energy from power generation, from the operation of electronic components, from biological processes or from solar radiation. Because of their advantages, such as long life, and low mass and power requirements, two-phase systems have been the foci of attention for a long time. OBPR will investigate a range of approaches such as multi-phase heat pipes, capillary and mechanical pump loop heat pipes, and electro-hydrodynamic devices in order to improve the heat rejection capacity and reliability, and to lessen mass and volume requirements.

NASA’s missions require propulsion systems that can extend to the outer reaches of the solar system and beyond. While present-day technology can provide propulsion systems that can achieve those goals, they are relatively low in efficiency, resulting in trip times that are much too long and in limited payload size and complexity. In particular, significant accomplishments in materials technology are required to achieve the efficiencies that will make future propulsion systems viable. For example, OBPR will carry out fundamental materials’ science research to support technological advances in electrode materials for electric propulsion engines, in fuel material, reactor cladding, and heat radiator low-mass materials for nuclear propulsion, and in advanced low-mass materials for solar sails and inflatable structures for aero-capture technologies.

Fabrication of components during space missions will be one of the key elements for developing a self-sufficient space exploration capability. Specifically, in-space fabrication could reduce reliance on spare parts supplied from earth and will enable production of components and deployable structures that cannot be launched from earth either because they are cost or size prohibitive or because they cannot withstand launch loads. Fabrication conducted within the environment of a spacecraft needs to consider parameters such as variable gravity levels, different pressure and temperature conditions. Research is needed in these critical areas of advanced materials and in-space fabrication processes: habitat and deployable structures, thermal protection systems, electronic and photonic materials, and dual or multi purpose materials. The need for research includes the study of fabrication and assembly of parts and devices outside the confines of a space vehicle to add large elements to an existing outpost, the fabrication of mission-specific devices to enhance safety or effectiveness. These "*free space*" operations present a unique set of technical challenges created by the space environment. High vacuum, intense radiation of many types, large temperature gradients, high momentum objects and levels of gravity ranging from microgravity to localized artificial gravity characterize this environment. The need for a capability to process materials and construct objects of large dimension under such extreme conditions demands a thorough study of the behavior and properties of materials that will enable imaginative solutions to develop robust technologies.

Roadmap: What technology must we create to enable the next explorers to go beyond where we have been?

Objective	2003-2007	2008-2012	2013-2017
R & T to reduce up-mass, volume, and power of next generation highly reliable spacecraft sub-systems	• Basic research in areas of air revitalization, water recovery, food production and processing, and solid waste processing • Integrated testing of subsystems • Multi-phase transport and flows modeling and experiments	• Validation of life support technologies in relevant environments • Development of integrated systems models and performance of relevant trade studies • Improved fluid & thermal system designs for low-g • Synthesize and process improved materials	• Life support technologies and subsystems that are lighter than a factor of three as compared to the baseline ISS systems • Expertise for deployment of next generation sub-systems
Research required to develop safe, efficient, and economical in-space transportation to go beyond LEO	• Low-g fluid management for propulsion systems/models & experiments • Tools for advanced materials design	• Data and expertise for next generation system design for low-g • Synthesize and process improved materials for propulsion systems	• Expertise for deployment of next generation sub-systems
Research required to provide affordable, abundant power for operations, including in-situ planetary resources	• Low and variable g processes and reactors for in-situ production of oxygen, water, and fuel • In-space and in-situ fabrication processes	• Small-scale ISS tests and model development for varying g • Develop fabrication technologies for specific elements / ISS tests • ISS experiments to obtain benchmark data for model verification	• Implementation of small-scale model systems • Test and validate prototype systems on long duration space flight
Research and Technology to optimize crew performance and productivity during extended isolation	• Research in areas of scheduling, crew behavior, optimal performance assessment, human machine interfaces, and augmented reality	• Develop tools to optimize human performance in enclosed environments. • Test tools on Shuttle/ISS	• Human performance optimization tools for space travel that are comparable or better than Earth work environments
Research in automated sensing and autonomous controls for a safe and healthy crew environment	• Basic research in development of sensors for fire, chemical and microbiological monitoring • Basic research in autonomous control systems • Improved low-g test methods for materials flammability • Improve radiation transport codes	• Validation of next generation/miniature sensors in relevant environments • Integration of sensors with controls systems • Low-g validation of test methods/ Particulate and gas sensors for early detection • Certify new materials for radiation shielding	• Miniaturized sensors and control systems that can monitor the entire chemical and biological environment to enable long duration missions • New materials incorporated in spacecraft systems

Question 5: How can we educate and inspire the next generations to take the journey?

Quotes:

Sean O'Keefe, June 2002: "NASA's missions once inspired a generation to explore the stars and race for the Moon. While our missions and points of destination have changed, the same challenges remain very much a part of our future. We accept our responsibility to inspire a new generation of explorers and we will succeed in ways that only NASA can."

President John F. Kennedy; Address at Rice University on the Nation's Space Effort; Houston, Texas; September 12, 1962: "Many years ago the great British explorer George Mallory, who was to die on Mount Everest, was asked why did he want to climb it. He said, "Because it is there." Well, space is there, and we're going to climb it, and the moon and the planets are there, and new hopes for knowledge and peace are there. And, therefore, as we set sail we ask God's blessing on the most hazardous and dangerous and greatest adventure on which man has ever embarked."

Primary Outputs:

Materials for the Professional Development for Educators that accomplish the following: Increase number of educators with comfort level of teaching science; Increase science proficiency of practicing educators; Increase in classroom use of educational space research lab simulations.

Development of Experiences and Materials for Students and Classroom Use that increase the use of science activities in mainstream and alternate school environments; provide accessibility of materials by all students with no limitations based upon resources, race, class, gender, or ability; and increase student interest in science and science-related careers

Community Collaborations that reinforce formal and informal science learning; bring space research to communities in innovative mediums; increase scope of program's reach; reach non-traditional learners; engage entire local, regional communities as participants in space research; and provide venues to communicate message to media.

Concerted and pro-active leadership in Higher Education programs that advance selection of careers in math, science, engineering and technology; and that enhance research and academic infrastructure and expand faculty and student involvement in the NASA research and education community.

OBPR is evolving towards a robust public outreach program involving media (print and broadcast), feature stories in refereed journals and general public literature (Times, Newsweek, USA Today), news conferences releasing important OBPR research findings, involvement in professional conferences particularly where association professional objectives intersect OBPR research program goals, evolving communication technology to optimize reaching target audiences, targeting non-traditional audiences to communicate OBPR's research messages, and other activities geared towards informing the local, regional and national general public.

Desired Outcomes:

Independent recognition that the Enterprise's unique space research and communications inspire achievement of academic excellence, positively influence the choice of science, math and technology careers, and increase the scientific literacy of our nation's citizenry. Through outreach initiatives, the professional and general public will develop an ongoing awareness of not only what takes place, but why such research is taking place and how space research can benefit life on Earth.

Description:

There is an interesting dichotomy within the public regarding space: the public has had a longstanding fascination with space but does not have a sufficient understanding of space research and how such research bears upon life on Earth.

For most people, NASA represents a Shuttle launch and an orbiting Space Station. Many recall the fascinating images from the robotic mission to Mars. Some recognize the magnificent images taken from Hubble. Today, few can describe the research taking place in the International Space Station, or how space research has had or can have impact on the daily life of the Earth's inhabitants outside the fields of communication and remote sensing. Our challenge is to convey this information to a diverse audience: the technical, professional and general public, the major stakeholders in NASA's future including that of OBPR, and especially to educators and the education community.

In recognition of the magnitude of this challenge and to the distinct differences in approaches to the varied audiences, OBPR supports a Public Outreach Program and an Educational Outreach Program.

Educational Outreach: It is a known fact in academia that nations with higher educational scores tend to have more inquiry-based, experiential classroom learning. The ultimate science educational goal is to enable students to learn with understanding. Understanding science involves making connections between people, objects, and real-world applications. OBPR's Educational Outreach Program will continue to bring to the classroom real-time exchanges, cutting-edge research information, and relevant learning materials. Listening to and enabling quality communications among the "experts" remains the foundation for all OBPR Education Outreach Programs.

Educational outreach products must be content-rich, standards-based, and respond to the requests and advisement of the educators and students. OBPR recognizes that educational outreach extends beyond classroom walls and includes both formal and informal opportunities to learn for all ages, in a variety of environments. OBPR is committed to bringing "space to school" to all students, aided by the production of bilingual materials and the use of established means to reach rural communities, special needs students, home schooled students and non-traditional students, as well as those of the mainstream schools.

The OBPR Educational Programs will be directed towards four significant educational components - Professional Development of Educators, Development of Experiences and Materials for Student and Classroom Use, and Community Collaborations and Higher Education. The world of education revolves around the establishment and acknowledgement of 'best practices", and OBPR has defined these for each of the three components. Interwoven throughout all programs will be four intents - extending our reach to underserved populations, expanding our integration of technology and use of digital delivery mechanisms, engaging learners as participants, evaluating and benchmarking our impact. The focus of the content will be the Biological, Physical Sciences, and Commercial flight research that takes place aboard International Space Station, other spaceflight missions such as those on the Shuttle, and the on-going ground-based research.

Public Outreach:

- *What is meant by outreach to the public?*
- *What constitutes the public as an audience to reach?*
- *Why is this important to OBPR's mission?*

The primary intent of public outreach is to communicate OBPR research objectives and accomplishments, not only what is taking place but why such research is taking place and why it is important, to a broad spectrum of communities. The audiences for OBPR public outreach are as diverse as the research itself. OBPR's target audiences include technical and professional associations whose membership and professional interest closely parallels OBPR research disciplines; public advocacy and information groups serving the needs and interests of their members such as AARP; agencies such as the National Institutes of Health sharing complementary agency objectives as a basis for potential collaboration; and the important, large, but less defined community of the general public. OBPR must establish and maintain channels of communication with these groups and bring to them the results of OBPR's ongoing and evolving research. Communicating diverse research goals to a range of communities of varying levels of technical background is a daunting task but an essential and mandatory one: under the 1958 Space Act as amended, the Administrator is charged with the widest practicable dissemination of agency results. It is also the right thing to do; OBPR has an obligation and commitment to describe to the public the return from their investment in space. To inspire the public, we endeavor to make space research a part of their lives.

Education Outreach: A Roadmap

Objective	2003-2006	2007-2011	2012-2016
A model program of Educational Outreach Professional Development Opportunities in the format of Seminars, Educator Networks & Conference Presence	• Seminars qualified for continued education credit • Discipline Educator Networks • Focus groups for educational materials	• Produce strong collaborations with Education Associations • Increase space research articles in Education publications	• Provide benchmark data on impact to educator science proficiency • Provide benchmark data on impact to classroom use of science labs
Student materials that engage students in the process of space research are available to all students	• Home School Initiative • Latino initiative • Form collaborations for Production of digital access programming • Digital Access Initiative	• Education Briefs plus digital component • Established, effective reach to under-represented students, special needs, with documented feedback	• E-missions • Interactive links with crews • Validation of use of materials in mainstream and alternative learning settings
Partnerships with and support from organizations that share the core value of increasing our nation's scientific literacy and achieving academic excellence	• Collaboration with USDA for Space Agriculture in the classroom program • Collaboration with the NASA Aerospace Education Services Program (AESP) • Collaboration with National Space Grant	• Establish OBPR working laboratory with informal institutions • Ongoing collaborations with distance learning networks	• Dedicated collaborations for exploration missions • Data validating collaboration impact with informal institutions
Expanded student numbers directed toward science careers	• Support undergraduate Spaceflight and Sciences Training Program, Graduate Student Research Program, Resident Research Associateship • Partner with Minority University and Research Program, Hispanic Serving Institutions, Tribal Colleges and Universities • Develop plan to track student progress	• Increase the number of GSRPs and RRAs • Introduce PI research into curriculum • Increase active presence of students at conferences and programs	• Dedicated collaborations for exploration missions • Double the number of students involved with OBPR Higher Education programs

Public Outreach: A Roadmap

Objective	2003-2006	2007-2011	2012-2016
Publications, Print and On-line	• Space Research newsletter readership > 50,000 • Science@NASA expands in scope for education/public audiences	• Space Research newsletter readership > 100,000 • Science@NASA expands to multi-language stories	• Space Research newsletter readership > 150,000 • Science@NASA has global on-line readership
Exhibit Participation	• Emergent technologies (e.g. holograms) utilized • Conference participation doubled over 2002 level • New segments of public reached	• Showcase new research initiatives & capabilities from ISS • Conference participation doubled over 2007 level	• Exploration mission interactive links with exploration crews • Next generation ISS concepts and plans
Media	• Highlights in prestigious journals and public magazines • Broadcasts on vested telecommunications' networks (NPR, Discovery, Natl. Geo)	• Increase frequency of coverage of ISS research results • Showcase new research initiatives • International outreach campaigns	• Dedicated programming for exploration missions • Interactive links with exploration crews
Partnerships	• Collaboration with NIH, NIST, DOE, etc. • Begin ties with community organizations, clubs, non-traditional venues	• Active role in organizations with parabolic and flight opportunities • Expand ties to BIO, ASCO, NMA and AARP	• Partnership involvement with outreach for exploration mission

Accomplishing the Mission

> *Harold Varmus, former head of NIH and Nobel Laureate: "Medical advances may seem like wizardry. But pull back the curtain, and sitting at the lever is a high-energy physicist, a combinational chemist or an engineer."*
>
> *R. Boyer, Concepts in Biochemistry: "Two separate and distinct avenues of scientific inquiry have led to our current state of biochemical knowledge. One avenue can be traced through the physical sciences and emphasizes structural characteristics of biomolecules. This approach has applied the basic laws of physics and chemistry to explain the processes of the living cell…The other avenue traveled by the biologists, especially microbiologists, cell biologists, physiologists, and geneticists, is characterized mainly by a study of cell organization and function…The two avenues of study converged in 1952 with the announcement by James Watson and Francis Crick of the double helix structure for DNA. Here the application of physics (crystallography), chemistry (structure and bonding), and biology (storage and transfer of genetic information) all came together to help solve what was the most exciting and complex biological problem at that time: the structure of the genetic material, DNA. The growth of knowledge in biochemistry since that time has been explosive."*

In order to accomplish our Mission, the traditional OBPR discipline-oriented approach will be updated to foster interdisciplinary research, cutting across biology and the physical sciences and engineering. This approach parallels what has proven successful in the external research community. With the mapping of the human genome largely complete, the Twenty First Century is being hailed as the century of biology. The field of biology has begun to experience a quantum leap in new knowledge in part through the infusion of sophisticated quantitative tools of physical sciences. In addition, the systematic application of inter-disciplinary mechanistic approaches promises to produce an even more rapid growth in knowledge necessary to permit a priori prediction and control of behavior of living systems and organisms.

In OBPR, we are committed to interdisciplinary research because of its untapped potential to accelerate and improve our research accomplishments. For example, fluid physics and biology share a relationship that is deeply symbiotic yet largely unexplored. Life on Earth is believed to have started in the fluid phase and the latter is essential for sustaining life. Most processes in living organisms, transport of nutrients, conversion of nutrient to energy, intercellular and intracellular signaling and rejection of waste products take place in the fluid phase. In spite of large gains in knowledge that have been realized in biological sciences, many of the fundamental mechanisms in biological systems are yet to be understood.

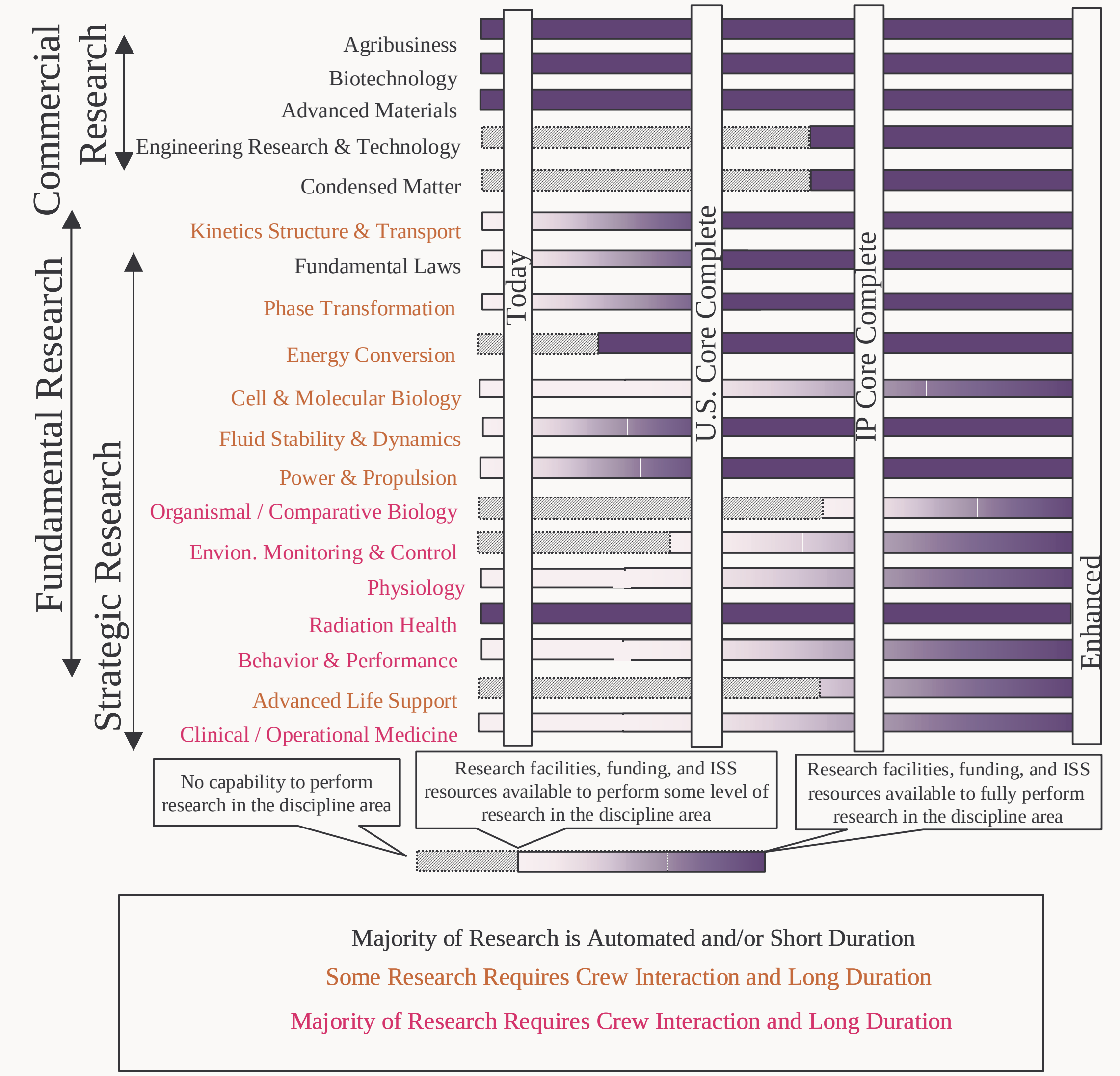
There is no question that NASA has amassed a tremendous capability in the biological and physical sciences and engineering disciplines through its past achievements. Too often, artificial barriers between technical disciplines, programmatic divisions, and organizations have impeded progress. Now OBPR will use its capabilities through interdisciplinary research to realize even greater achievements in the future.

A Ten-Year Model: The Use of ISS

The agency's vision for the International Space Station is that "it serves as a human outpost in space bringing nations together for the benefit of life on Earth and beyond." Its mission is "to enable revolutionary discoveries and establish the permanent international presence of humans in space to advance exploration of our solar system and enable commerce in space."

The FY 2001 VA-HUD IA appropriations bill, H.R. 4635, Conference Report (House Report 106-988) directs that NASA "develop a 10-year plan for all research efforts related to the International Space Station (ISS), including operational needs." NASA believes that this 10-year research plan requirement will be fulfilled by submitting the report specified in the current Senate VA-HUD-IA Subcommittee Report for FY 2003, S. 107-222, which directs NASA to submit a joint Code M-U report on the implementation of ReMaP. ReMaP considered only the research program of the OBPR, and the planned implementation by OBPR of the ReMaP recommendations has been vetted with and endorsed by various advisory committees. The ReMaP recommendations have been put into a strategic context for OBPR's research, which is described in this Research Plan and its appendices. To further fulfill the Congressional requirement, the detailed 10-year operational needs for the ISS-based research of not only the OBPR but all of the International Partners are described in an Appendix of this Research Plan. Integration of selected research into the ISS Flight Program requires careful coordination of research requirements, multi-use facility development and deployment, unique hardware development and availability, and available ISS resources.

The capability and readiness to perform OBPR's high priority research is dependent upon the configuration of the ISS. Shown here are graphical representations of that ability as a function of the configuration, along with qualitative classifications of the nature of that research, as to its reason for utilizing the ISS and its contribution to OBPR's strategic, fundamental, and commercial research thrusts.



The US Core Complete configuration can support a strong program in ReMaP Priority 1 fundamental research in physical sciences and commercial research. This configuration provides, beyond what is there today our major facilities for support of fluids, combustion, and materials research and the Human Research Facility-2 for biomedical research. In addition to the previous areas of emphasis, the IP Core Complete configuration can enable OBPR research in fundamental biology and fundamental physics. This configuration provides access to the Japanese Exposed Facility, a large centrifuge with associated specimen habitats (cell, animal, plants, etc.), additional rack volume, and access to JEM and COF research facilities for collaborative research. The enhanced configuration allows OBPR to pursue an emphasis in strategic research as well as the ISS partnership to realize the full potential of the ISS as a research platform. This configuration may provide an expanded number of astronaut crew, as is commonly required for statistically significant biomedical research, who will also provide additional time for conducting research, and to provide additional scientific expertise.

Setting Priorities for the Use Of ISS

As several advisory committees have noted, a need to set priorities for OBPR's ISS resources often develops, owed to the changing nature of ISS capabilities, fluctuations in budget, and in recognition of the large number of "Priority 1" research areas identified by the ReMaP Task Force. OBPR has established and already applied an initial strategy to prioritize its ISS research. To the first order, our ISS requirements have reflected this strategy, which includes the following considerations, in priority order:

1. Research can only be performed on ISS -- requires crew intervention/involvement and long duration microgravity exposure
2. Research is required to achieve the Agency's strategic vision and is consistent with and required to meet the goals outlined in the OBPR research plan
3. Research is done most effectively on the ISS, either from a cost perspective or a time perspective, given the nature of the ISS capabilities

If further prioritization is needed, a more complete set of decision rules will be applied. This set is being drafted, and presently includes:

- REMAP Priority
- Research can only be performed on ISS
- Strategic Value
- Scientific Return
- Terrestrial Benefit
- Timeliness
- Readiness for Flight
- Vehicle Resources Required

Given the time-phased availability of both ISS research facilities and ISS resource capacity, however, the requirements are and will be time-phased to maximize the scientific return from the ISS. It should be noted also that these considerations are primarily applicable to OBPR's use of the ISS. OBPR uses a broad array of ground and space-based assets to carry out its research, as shown below.

Ground-based research:
- Laboratory studies
- Drop towers
- Acceleration devices (research centrifuges and linear sleds)
- KC-135 / parabolic flights and sounding rockets
- Analog studies (bedrest, isolation chambers, etc)

Space-based research:
- ISS (primary platform)
- Shuttle (dedicated missions or while attached to ISS)
- Free-flyers (LEO and beyond)

Innovations in Spaceflight Investigation Processes

Throughout all phases of preliminary design and development of the International Space Station (ISS), the research sponsoring organizations of NASA have sought innovative methods to continuously improve the processes associated with completing research investigations in space. In concert with advice from standing and ad hoc committees of both the National Research Council and the NASA Advisory Council, we continue to incrementally reduce the cost and schedule requirements for flight investigations through advances in planning, development and operations. These innovations are briefly summarized below.

Express Rack and Pallet Program – Simplifying the Flight Hardware Interface:

At the close of the ISS preliminary design phase, and in the wake of a rising call for application of a "Quick is Beautiful" principle to payload integration, we systematically gathered requirements from the user community at large and designed rack and pallet architectures to accommodate multiple small scale investigations through a streamlined process. The Express Rack and Pallet Program emerged and has become a mainstay in our current ISS utilization plan. Through this program, a common payload accommodations infrastructure was put in place with standardized physical interchangeability and functional interoperability at the sub-rack and sub-pallet level. These features allow greater flexibility in transporting payloads to space and increased opportunities for deployment in any ISS partner element on the station. Leveraging from design of the International Standard Payload Rack (ISPR), the Express rack provides standard interfaces for research lockers and drawers, and a corresponding 12 – 18 month flight integration process. The Express Pallet infrastructure, upon completion, will accomplish similar objectives for externally attached payloads.

Payload Operations Architecture – Reducing the Overhead Cost of Operations:

As the ISS entered the operations phase, attention turned to the high overhead costs associated with conducting payload operations. A Payload Operations Concept and Architecture Assessment Study (POCAAS) was commissioned to investigate opportunities for improvement. The external study team, composed of prior astronaut payload specialists and retired space operations directors, audited the cost and work structure and provided sound recommendations for significant changes. The pivotal change was recognition of the continuous operating mode of the ISS, as compared to the periodic mission mode of the Space Shuttle. This factor translated into a continuous payload operations concept, which was not as labor- or document-intensive as prior experience. As a direct result, a 15% reduction in the cost of payload operations will be implemented during FY 2003 and further efficiencies are planned as the payload operations transition proceeds.

NGO Utilization Management Concept – Organizing for Success:

A series of three external and two internal studies were undertaken in order to carefully evolve an innovative concept for management of ISS utilization, and ensure all perspectives were brought to bear on this mission critical endeavor. We are now prepared to confidently recommend the most productive approach and proceed with a competitive outsourcing that will make the vision a reality. The prospect of a non-government organization (NGO) for ISS utilization management (a.k.a. the ISS Research Institute) opens up new opportunities to achieve the most efficient and effective method possible for this unprecedented science and technology asset. It will allow us to engage the fullest possible capacity of our nation's intellectual resources across the scientific, technological and industrial communities and realize the full potential that the ISS has to offer.

Guiding Principles

In order to accomplish our mission and realize the Agency's Vision, we will employ the following guiding principles.

Why NASA? Why OBPR?

In the formulation of the program content, two key questions we ask ourselves before establishing support for any new initiative or individual investigation are:

- Why is NASA the appropriate leader or sponsor of this effort?
- Why is OBPR the appropriate organization within NASA to lead, sponsor, or participate in this effort?

While such questions may seem obvious, they are necessary reminders that the breadth of interesting ideas for scientific research and technological development far exceeds what NASA and OBPR can and should do. It is easy to want to participate in many ventures that are intriguing scientifically or emerging technologically. The decision for NASA and OBPR involvement derives first from the guiding principle that NASA and OBPR have a unique charter, capabilities and resources that it can apply to the endeavor.

OBPR Principles:

In addition to the assumed compliance with Federal and Congressional policies, we also will utilize the following guiding principles (not in any priority order) to implement the OBPR research program:

- Consistent and frequent use of broadly announced, competitive solicitations for basic scientific research
- Use of peer reviews in all aspects of the program – from individual investigations to overall program assessment
- Maximization of use of available space flight resources (existing hardware, flight opportunities, allocated crew time, power, etc.)
- Assurance of balance among the various scientific and technological disciplines and program goals
- Assurance of the appropriate balance between basic science, strategic and commercial research, and technology development

- Alignment with NASA's emerging missions and thrust areas, with such areas sometimes conceived by OBPR
- Identification of end uses and users for all applied research and technology development, ideally with endorsement and commitment to apply results by those users
- Communication and interactions across OBPR divisions
- Communication with other agencies and national laboratories to avoid duplication of effort and to achieve complementary goals
- Communication with external scientific and technology development communities, particularly in the advisory process
- Strong support for universities for essential, long-term research talent
- One NASA: demonstrable integration of the NASA research centers with HQ in formulating and implementing the OBPR program

Performance Metrics

> *Freeman Dyson: "The science-oriented approach measures success and failure of missions by looking at the quality of their scientific output…It asks of each mission not merely the easy question, "Did it work?" but the more difficult questions, "So what?" "What did we really learn""*
>
> *Freeman Dyson: "…Scientifically speaking, there is such a thing as total failure of a mission, but there is no such thing as total success. A successful mission will raise new questions as often as it answers old ones."*

OBPR is committed to the definition and implementation of metrics to track our performance toward achieving the products (outputs) described in this plan, as well as reaching the desired outcomes. These currently are in development, and will be included as part of the OBPR Enterprise Strategy. As suggested in the quotations by Freeman Dyson, the "return on investment" for some aspects of scientific research is difficult to anticipate, and will require a longer time after the initial research is performed to determine.

Summary

Freeman Dyson: "The American space program is at its most creative when it is a human adventure…"

The human exploration of space is one of the great voyages of discovery in human history. This is why it is both so compelling and so challenging. It must be anticipated that explorers will encounter many unforeseen difficulties as well as many opportunities that are beyond our current vision. We must make sure that they have the tools and knowledge available to respond to the challenges they encounter in creating habitats and using the resources available to them in new environments. The biomedical, biological, scientific and engineering research communities bring critical talents to this effort, and represent a segment in the national fabric of science, engineering, and education that must be enlisted in order to assure the long-term success of the Enterprise. This community has a long history of participation in other mission-driven research efforts. In collaboration with NASA's own researchers, this community will continue to be the centerpiece upon whom we rely to develop research and technology that has high scientific merit, significant terrestrial benefit and/or direct relevance to NASA's missions.

Explorers hundreds of years ago faced severe risks to their health, their ship, and their cargo. Our research must enable the current and next generation of space explorers to prevent and mitigate the risks that they will face.

Appendix A: Descriptions of OBPR Research Thrusts (per OBPR-prepared Material for ReMAP Task Force)

Behavior & Performance
Research focused in six areas: 1) perception and cognition, 2) human physical performance, 3) personal, interpersonal and group dynamics, 4) habitability, e.g. human factors – how the person responds to the human-machine interface, 5) circadian rhythms, and 6) advance technology development in these areas.

Clinical/Operational Medicine
Research to define medical risk, test proven ground medical treatment and technologies for use in spaceflight, develop new medical preventatives or rehabilitation therapies for use by astronauts in space or on their return to Earth, and the development of advance technology for use in space for diagnosis, biomedical technical training and continuing medical education, and therapeutics.

Environmental Health
Applied research to study barophysiology, microbiology and toxicology and to develop new technologies in these areas. The purpose of this program is to better understand the specific risks, and how to prevent and treat potential health problems that occur because of the microgravity, and the confined and isolated living quarters.

Integrated Physiology
Inter-system research on the physiological and behavioral alterations that occur during spaceflight. The purpose is to define the systemic changes that occur to other organs by perturbations in another organ system, determine the mechanisms for these changes and the development of countermeasures or treatment modalities to reverse or prevent the deleterious effects associated with space flight. Examples include "how spaceflight induced physiologic responses of the vestibular system cause problems in the autonomic and cardiovascular systems" or "how changes in the digestive tract effect the maintenance of the musculoskeletal system.

Organ System Physiology
In addition to classical physiologic research, research to understand the underlying molecular, genetic, and cellular factors, and other underlying processes that result in spaceflight changes of a single organ and the development of "countermeasures" to prevent, slow or recover from maladaptive spaceflight induced changes to the specific organ. Examples include organ disciplines including cardiovascular, bone, muscle, vestibular, etc.

Radiation Health
Research to determine the risk and prevention of health problems induced by space radiation. Specifically research that will reduce the uncertainties associated with predicting the excess risk of carcinogenesis resulting from radiation exposure during space flight. Support ground-based research studying the biological effects of heavy ions using the NASA facility at Brookhaven for the evaluation of risk factors to radiation-induced carcinogenesis and other radiation-induced health problems. Studies will center on genetic biological research, bioengineering and radiation

protection through research in radiation physics and shielding materials as appropriate and advanced technology development for the diagnosis, and prevention of radiation damage to space travelers.

Advanced Life Support

Advanced life support project conducts R&TD to provide: temperature and humidity control; atmosphere purification, and revitalization; water recovery and management; waste management; and food management. Integrated life support systems testing and validation has also been conducted by the ALS project.

Environmental Monitoring and Control and Advanced Environmental Monitoring and Control

EMC research and technology development encompasses monitoring the internal environment of a human occupied spacecraft, including the atmosphere, water supplies, and all surfaces. Monitoring implies continuous oversight of the status of these areas over time to ensure that conditions are maintained within acceptable limits and Control implies some form of feedback to the systems responsible for maintaining each parameter.

Extravehicular Activity and Advanced Extravehicular Activity

Extravehicular activity is work conducted outside the pressurized volume of a crewed space vehicle/facility. The EVA equipment consists of: the spacesuit, the primary life support system (pressurized oxygen, ventilation, and removal of CO2, water vapor, and trace contaminants), thermal conditioning, and the tools (including robotic tools) that enable the EVA crewmember to accomplish the necessary tasks.

Space Human Factors Engineering

Human factors focuses on the role of humans in complex systems, the design of equipment and facilities for human use, and the development of environments for comfort and safety. Subject areas for human factors research include ergonomics, biomechanics, anthropometrics, workload, and performance. Design of systems and operations for human activities in space is called space human factors engineering.

Cell and Molecular Biology

Research in this area addresses how basic cellular function and properties (e.g., mechanoreception, signal transduction, gene regulation and expression, proteomics, integrin function and structure, cytoskeletal structure and function, etc.) may be directly or indirectly impacted by altered gravitational force and other space-related effects. Of particular interest are molecular and cellular studies associated with the physiological changes seen in whole animals in response to the space environment.

Developmental Biology

Research to determine the role of gravity in normal development and function, how gravity and other aspects of the space environment may affect the capacity of organisms to reproduce, and the mechanisms by which subsequent generations are affected. Of particular interest is the development of systems and structures involved in gravity sensing and response.

Evolutionary Biology

Research to understand the capacity for terrestrial organisms to evolve in the novel environment of space, and the role gravity has played in terrestrial evolution.

Gravitational Ecology
Research to understand how the space flight environment might affect the structure, function, and the evolution or stability of ecosystems, particularly as they might relate to spacecraft or planetary habitats.

Molecular Structures and Physical Interactions
Research that emphasizes the physical effects of the space flight environment, such as static boundary layer effects on gas exchange, changes in heat transfer, lack of convective fluid movements, and alterations in diffusion-limited metabolic processes, on the functioning of single-celled and multi-cellular organisms.

Organismal and Comparative Biology
This element elucidates the effects of chronic exposure to altered gravity and/or other space-related factors on normal physiology, metabolism, and performance of animals and plants, and compares or contrasts them among different organisms.

Condensed Matter and Quantum Phenomena
Cooperative phenomena in non-equilibrium systems; atom laser studies, low-temperature atom condensates.

Fluid Stability, Dynamics, and Rheology
Fundamental aspects of fluid behavior in low gravity, including interfacial phenomena and multiphase flows.

Fundamental Laws and Benchmark Data to Test Theories
Tests of fundamental laws of physics and integrated theories requiring innovative experimental techniques. Research spans second order phase transitions in low temperature physics, relativity experiments using high accuracy atomic clocks, and fundamental aspects of materials research
and combustion science.

Kinetics, Structure, and Transport Processes in Physico-Chemical Systems
Transport phenomena, kinetics, and non-equilibrium processes. Nucleation (of bubbles, soot, crystallization, etc.); rates of chemical or metabolic reactions (during combustion or cellular activity). Formation of particles such as fullerenes and soot.

Phase Transformation, Pattern Formation, and Self-Assembly in Physico-Chemical Systems
Physics of processes leading to order and structure in systems of technological interest: solidification processes in metals, defect formation in crystalline materials, self-assembly in colloidal suspensions, dynamics of foams and granular systems.

Thermo physical, Physical-Chemical, and Biophysical Properties
Transport and thermodynamic data on materials and systems of technological importance.

Bio-inspired and Microfluidics Technologies
Interdisciplinary research projects bringing expertise from biology, physics, chemistry, and engineering to focus on understanding the synthesis and function of macromolecular assemblies. Application to new experimental methodologies for ISS and other space-based research stressing miniaturization and automation.

Cell Science and Tissue Engineering
Applications of low-shear stress culture technology for three-dimensional mammalian cell systems; effects of mechanical stresses on cell systems. Enhancement of technology for three-dimensional tissue culture and engineering using the NASA Bioreactor as a foundation.

Energy Conversion and Chemical Processing
Combustion research on problems of energy- and environmentally-related interest.

Materials Synthesis and Processing
Reactive processes for synthesis of novel materials, including carbon nanostructures and ceramics for biomaterials applications.

Structural Biology
Micromechanics of protein crystal growth of biological macromolecules and factors controlling crystal quality; development of technologies for obtaining high-diffracting crystals of scientific interest.

Biomolecular Systems Technology and Sensors
Integrated research projects developing technologies to monitor biological signals and processes relevant to health care, cosponsored by the NIH/NCI

Fire Safety, Spacecraft Fluid System Engineering Research
Ignition and propagation of fires in low-gravity; detection and extinguishment technologies; prediction and control of normal and cryogenic liquid behavior in vehicle systems.

Mission Resource Production and Robotic Exploration
Research on gravity-dependent phenomena inherent to technologies required for planetary exploration missions. Basic research supporting mission architecture studies and chemical process design in non-Earth environments. Examples of currently supported projects include process studies on the separation of CO2 from the Martian atmosphere and the production of oxygen from lunar soils.

Propulsion and Power Systems
Heat transfer, thermal hydraulics, and high temperature/extreme environment materials relevant to vehicle propulsion and power technologies; microcombustion technologies for high density energy storage.

Radiation Protection
Interaction of space radiation and materials; prediction of crew radiation exposure; effective shielding strategies for crew and equipment.

Advanced Materials -- Commercial

Advanced materials research supports zeolite crystal growth for refining and chemical industries; dilute gas sensors; ceramic powders/non-oxide ceramic production; improved casting technologies and thermophysical properties research; optical fiber production for optoelectronic devices; chemical sensors, and; superconducting wires for transmission applications. This field
of research benefits from the use of microgravity to alter physical properties of the materials of interest and to provide insight into previously unknown phenomena, processes, and interactions.

Agribusiness -- Commercial

Agribusiness explores plant research under microgravity conditions to examine plant structure absent the force of gravity. Insights gained may lead to improved agricultural products. The research also adds to the base of knowledge in the fundamental science area of plant research and contributes to other fields of knowledge, such as plant-based pharmaceutical development.

Biotechnology -- Commercial

The Commercial Space Centers have established substantial research collaboration with pharmaceutical firms in the field of biotechnology. Pharmaceutical CSC partners include: Amgen, Bristol Myers-Squibb, Merck, Eli Lilly, BioCryst (spinoff of a CSC), Vertex Pharmaceuticals, Abbott Labs, Upjohn, Schering Plough, and other pharmaceutical firms presently affiliated with the CSC program. This research area has proven the broadest and most successful among the three areas of commercial applied sciences in terms of market support, industry investment and near-term potential for positive economic impact.

Commercial Engineering Research and Technology Development – 6 areas, as follows

Power Generation, Storage, and Transmission

Power systems have many applications. For example, advanced solar cells, batteries and flywheels, are of interest to a wide variety of industry partners for use in electric vehicles, uninterruptible power supplies, solar electric power generators, etc.

Propulsion

Space propulsion systems include electric, chemical, hybrid, and waste gas propulsion systems. Propulsion research will enable US satellite manufacturers and providers of launch services to be more competitive in an increasingly demanding market. Advanced propulsion systems would make it possible to use smaller and cheaper transfer stages and could greatly improve spacecraft reliability and lifetime.

Remote Sensing and Autonomous Systems

Remote sensing technology, such as hyperspectral imagery, has valuable commercial and scientific applications from environmental monitoring to identifying oil and gas deposits on earth to exploring and developing extraterrestrial resources. Autonomous systems that can rendezvous and dock enable refueling, maintenance, and orbit transfers of commercial and government satellites. These systems could greatly reduce reliance on ground control, providing advantages for scientific as well as commercial spacecraft. Greater autonomy would reduce the amount of tele-operation required in future planetary exploration.

Robotics and Structures

Robotic systems could be used in conjunction with or instead of astronauts to perform a wide variety of tasks, including inspecting, servicing, and repairing the station; manipulating and placing large objects outside the ISS, and servicing scientific experiments. Structures could improve the precision and reduce the weight of communications antennas, could lead to improved lightweight solar collectors antennas, and reflectors for low-cost robotic spacecraft, and could also reveal additional design options for ultra-light spacecraft.

Telecommunications

Technology development issues of importance to commercial communications satellites, including development and testing of phased array antennas, characterization of the on-orbit radio frequency environment, demonstration of high-data-rate communications, validation of complex on-board processors accomplishing advanced signal processing tasks, testing of optical communications devices, and deployment of unique antenna structures.

Thermal Control

Thermal control consists of devices for thermal transport and storage (heat pipes, two-phase pumps, phase change materials); refrigeration subsystems (thermoelectric devices and cryogenic coolers); advanced radiators (composites); and insulation.

Appendix B: Details Of A Ten-Year Model: The Operational Needs Of ISS

The International Space Station is an orbiting research laboratory with a growing capacity to host biomedical, biological, physics, space, earth, engineering, and commercial science. The agency's vision for the International Space Station is that "it serves as a human outpost in space bringing nations together for the benefit of life on Earth and beyond. Its mission is "to enable revolutionary discoveries and establish the permanent international presence of humans in space to advance exploration of our solar system and enable commerce in space." In fulfillment of the Congressional requirement, the detailed 10-year operational needs for the ISS-based research of not only the OBPR but all of the International Partners are described in this Appendix to the Research Plan.

Establishment of the ISS Research Resource Requirements Over a Ten Year Period

The overall ISS Research requirements are established through a coordinated effort of the members of the ISS User Operations Panel (UOP), which is drawn from NASA, the Government of Japan, ESA, CSA and RSA. At the request of the Heads of Agencies, the panel identified the research requirements for the ISS from 2004 through 2015. Requirements were gathered without regard to limitations in the capability of the ISS during assembly, although they were bounded by the previously negotiated research allocations in ISS International Partner Agreements.

Each partner's research activities are implemented when its elements are delivered to the ISS. As such, available resources in the early utilization stages are shared between NASA, RSA, and CSA. When the Columbus and Japanese Experiment Modules are added, all International Partners will begin to share the research capabilities.

The requirements collected by the UOP for 2004 through 2008 are projections based on selected investigations and assumptions on investigations that may be selected. The requirements for 2009 through 2015 are projections based on assumptions by each International Partner for the research demand within their communities. The following charts summarize the integrated product.

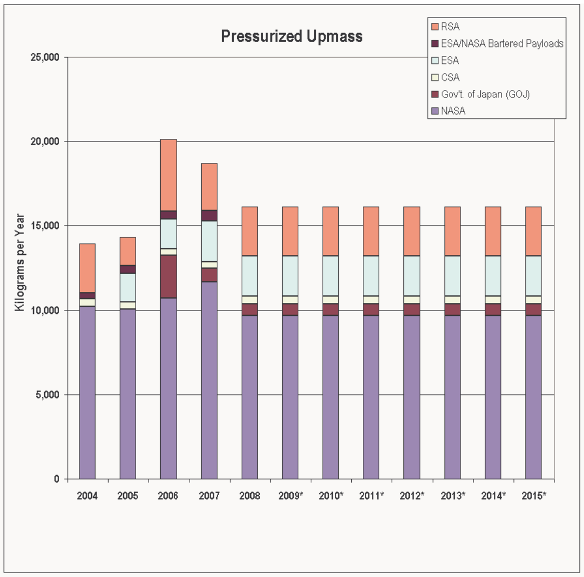


Figure 1. Pressurized Mass Requirements

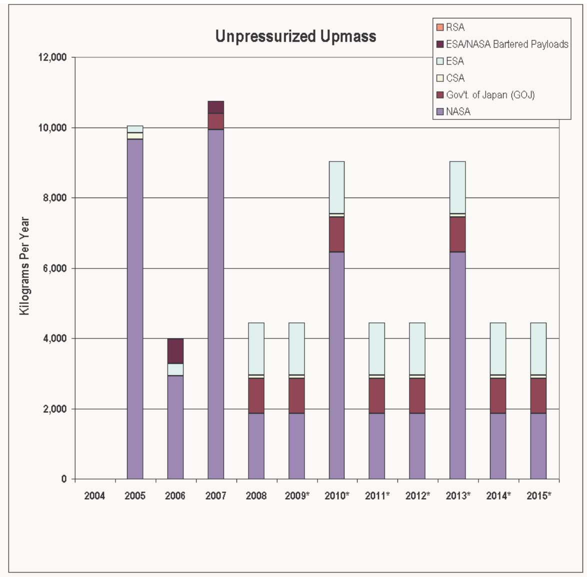


Figure 2. Unpressurized Mass Requirements

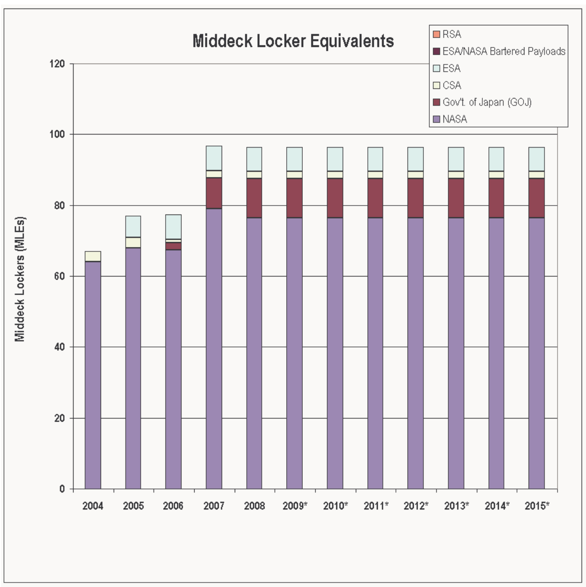


Figure 3. Perishable Sample Transport (Shuttle)

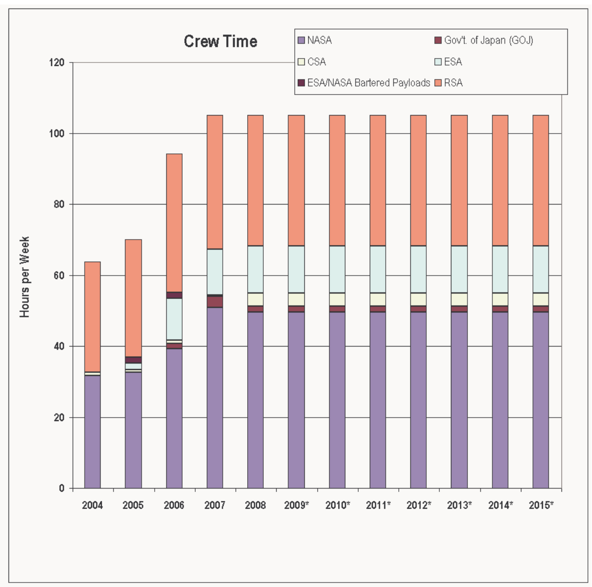


Figure 4. On-Orbit Crew Time Requirements

Available ISS Resources and Options for Optimization

The UOP's collective requirements were used to identify gaps or challenges in resource capabilities to meet the needs of the international research community. The gaps or challenges were identified as: available transport pressurized and unpressurized volume, mass transport of perishable samples (Shuttle middeck lockers); and on-orbit crew time.

Once identified, the challenges are addressed from both a programmatic and a research perspective. Assessment of options and improved delineation of requirements drive both the ISS Program Office and the research community toward a consensus path, one that is both acceptable to the research community and that can be accomplished within Programmatic constraints.

The available ISS resource capabilities to meet the research requirements are a function of budget, transport capacity, crew size, and requirements for ISS assembly, logistics, and maintenance. Each of these capabilities changes over time. Transport resources are often believed to be a rate-limiting capability, so they are addressed in two ways; 1) increased flight frequency to ISS and 2) optimization of resource allocations on existing flights. As an example of these considerations, a recent comparison between the research requirements for transport mass, middeck locker volume and crew time and the capabilities of the baseline ISS Program revealed that fewer than five flights per year creates a backlog of ISS research that continues to rise throughout the ISS lifetime. As such, a November 2002 proposed budget amendment included the funds to support an additional Shuttle flight each year to the ISS to augment the four flights that had been planned earlier. This fifth flight eliminates the backlog in this resource.

At the same time, NASA continues to investigate alternatives to optimize all resources on existing flights, providing more capacity for research. In all categories of resources, “trade-space” studies are conducted to increase utilization opportunities with the aim of fulfilling the requirements. A Multilateral Partner Program Team (MPPT) investigates alternatives for enhancing the Program’s capacity to meet the research requirements. The UOP also assesses the requirements against the options to identify the one that best meets the needs of the research community within the economic constraints of the Agency. The multilateral payload community meets biannually to reassess the utilization plans, incorporate lessons learned, adjust to resource availability, align the major facilities’ development and availability, and conform to changes in budget.

Implementation: Specific Research Manifesting on the International Space Station

Integration of selected research into the ISS Flight Program requires systematic coordination of research requirements, multi-use facility deployment, unique hardware readiness and available ISS, Shuttle and Progress resources. A *strategic* manifest plan is developed based on the prioritization set by the NASA Enterprises and the International Partners as they envision in their long-term objectives. A *tactical* manifest plan is also developed for the near-term, based on the cross-discipline prioritization of NASA research and coordination with the highest priority international research.

The Space Station Utilization Board (SSUB) within NASA approves the overall integrated strategic plan for NASA research on the ISS, and is the forum for resolving conflicts across disciplines. The current SSUB membership consists of the Associate Administrators from the Office of Space Flight, the Office of Biological and Physical Research, the Office of Earth Science, and the Office of Space Science, as well as the NASA Comptroller. The Office of Spaceflight integrates all Department of Defense, Education, Crew Earth Observations, International Partner Barter Agreements and ISS Detailed Test or Medical Objectives. The NASA Chief Scientist chairs the SSUB.

Based on recommendations from various studies, ISS Payload Tactical Plans are developed that intentionally exceed research allocations, identifying some of the research as candidates for specific flights. The development of this "research queue" postures experiments for late incorporation into the flight manifest, if additional resources become available. In addition, significant effort is devoted to identifying all possible conditions under which the research could be conducted in advance of the original manifest plan or under which experiments may be repeated within an increment.

The Payload Tactical Plans are presently baselined through ISS Increment 9. They encompass 85 investigations, representing 61 institutions across the world.

Multi-use Facility Development and Deployment

Several years ago, the ISS scientific community identified several major facilities that benefit multiple users and disciplines. The multi-use facilities engender significant budget and time for development, planning, and testing before they are ready for launch and subsequent use for research. Therefore, these major facilities are phased into the ISS flight Program consistent with science requirements, funding, available ISS resources and feasibility for ISS. The Office of Biological and Physical Research (OBPR) is responsible for development of these facilities. To ensure a stable development cost and schedule, the development schedule is not tied directly to the launch schedule. The facility racks are developed to meet a Flight Hardware Availability date, rather than a launch date. Manifesting of the racks on the ISS is then determined based on Space Station Utilization Board priorities, Flight Hardware Availability dates, and with the launch sequence schedules. The Express Racks were among the first facilities to be delivered to orbit, as they were the most versatile and least complex of all the multi-use facilities. The Human Research Facility, built in the Express Rack format, provides accommodation for high priority research in Bioastronautics. The Microgravity Sciences Glovebox (MSG) and the Minus Eighty Laboratory Freezer for ISS (MELFI) are facilities obtained through a barter agreement with the European Space Agency (ESA), in exchange for early utilization allocations from US resources. The MSG was installed in the US Laboratory in June, 2002. The next facilities to be installed are the MELFI and the Window Observational Research Facility, which allows high resolution photography to be taken through the U.S. Laboratory's research grade window. The remaining multi-use facilities will be ready for launch in 2004 through 2007. The Centrifuge Facility are projected to be ready for launch in 2007, with delivery of this complex facility under the responsibility of NASDA.

The instrument for tracking the launch schedules of the multi-use facilities is the Multilateral Payload Outfitting Model (MPOM). The MPOM identifies the flight for each of the facilities and is based on the latest assembly sequence. Figure 5 shows the draft MPOM associated with the Assembly Sequence update from October 2002. Note that the MPOM in years 2006 through 2008 is labeled "To Be Resolved (TBR)" pending discussions regarding Shuttle flight rate, other launch capability, and options for meeting the research requirements identified by the UOP. The MPOM is the foundation upon which we determine when the resources are available to support the overall utilization requirements as well as determine the research emphasis in the Research Announcements to utilize these facilities.